Draft

Groundwater Flow Model Report

Camp Allen Landfill

Naval Station Norfolk

Norfolk, Virginia

Prepared for

Department of the Navy

Atlantic Division

Naval Facilities Engineering Command

Norfolk, Virginia

Contract N62470-95-D-6007
CTO Task Order 156

Prepared by

CH2MHILL

Contents

Tables

Figures

SECTION 1

Introduction

A groundwater flow model of the Camp Allen Landfill has been developed to evaluate the existing system of 17 groundwater extraction wells operating at the site since November 1998. This model was constructed as part of the Scope of Work for CTO 156 – *Monitoring at Various Sites, Naval Base Norfolk*. Shown in Figure 1-1, Camp Allen is located in Norfolk, Virginia, near the central portion of the peninsula on which it lies.

File Path: c:\18gis\nsn\camod_figures2.apr

Note: Basemap adapted from Norfolk North quadrangle of the USGS 7.5-minute series topographic maps.

LEGEND

Camp Allen Landfill Areas

N

3000 0 3000 6000 Feet

Figure 1-1
Site Location Map

Camp Allen Landfill Groundwater Modeling
Naval Station Norfolk

CH2MHILL

SECTION 2

Hydrogeologic Conceptual Model

2.1 Hydrostratigraphy

The extraction system wells operating at the site screen the unconsolidated sediments of either the surficial Columbia aquifer or the underlying Yorktown–Eastover aquifer, as defined by the United States Geological Survey (USGS) Regional Aquifer-System Analysis (RASA) for the Virginia coastal plain (Meng and Harsh, 1988). The aquifers are separated by the Yorktown confining unit. These hydrostratigraphic units are described in the following in order of oldest to youngest.

The Yorktown-Eastover aquifer is comprised of the upper portion of the Eastover Formation of Miocene age, and the Yorktown Formation and lower portion of the Bacons Castle Formation, both of Pliocene age. The upper Eastover Formation consists of a grayish blue, fine- to medium-grained, well sorted, shelly sand, interbedded with occasional clay layers (Meng and Harsh, 1988). The Yorktown Formation consists of interlayered sands, sandy shell and shell beds, and silty clays. The lower portion of the Bacons Castle Formation consists of fine- to medium-grained, shelly sand facies. The Yorktown-Eastover aquifer is underlain by the St. Marys confining unit. Regionally, the Yorktown-Eastover aquifer dips and thickens eastward to a maximum known thickness of 296 feet in northeastern Virginia and 240 feet in southeastern Virginia. At the site, the aquifer thickness at minimum is on the order of 78.1 to 94.6 feet based on the known elevation of the aquifer top and the lowest elevation for the aquifer bottom, –120 feet msl, assumed from deep boring logs. However, it is unclear whether or not any of the deep soil borings or wells reached the bottom of the Yorktown-Eastover aquifer at the site. The aquifer thickness may be as great as 206 feet based on the average elevation of the top of the Yorktown-Eastover aquifer at the site and the aquifer top elevations and confining unit thicknesses reported by Meng and Harsh (1988) for underlying units.

The Yorktown confining unit is composed of the upper portions of both the Yorktown and the Bacons Castle Formations, both of Pliocene age (Meng and Harsh, 1988). Meng and Harsh (1988) describe this confining unit as a series of coalescing clay layers at or near the tops of the Yorktown and Bacons Castle Formations. The lithology of the confining unit varies from very fine sandy to silty clay, ranging in color from gray to orange or multicolored. The Yorktown confining unit dips eastward and generally thickens to the east to a maximum known thickness of 109 feet in northeastern Virginia. Based on boring logs for on-site wells, the Yorktown confining unit is laterally discontinuous and varies in thickness from 0 to 28 feet, with thickness generally increasing to the north and south. Where absent, the underlying Yorktown-Eastover aquifer is in direct contact with the overlying Columbia aquifer.

The Columbia aquifer consists primarily of surficial deposits of Pliocene, Pleistocene, and Holocene age, including sandy Pliocene deposits overlying the Yorktown confining unit and Pleistocene formations locally known as the Windsor, Charles City, Chuckatuck, Shirley, and Tabb (Meng and Harsh, 1988). In general, the sediments of the Columbia aquifer consist of tan to rusty orange, fine to coarse-grained sands and gravel interbedded with silts and clays. This aquifer generally thickens eastward, but the thickness varies locally due to surface erosion. Across the site, the Columbia aquifer varies from approximately 20 to 40 feet in thickness. Shown in Figure 2-1, the contoured bottom elevations for this aquifer, taken from on-site boring logs, vary in elevation from approximately -10 to -34 feet msl with 24 feet of relief.

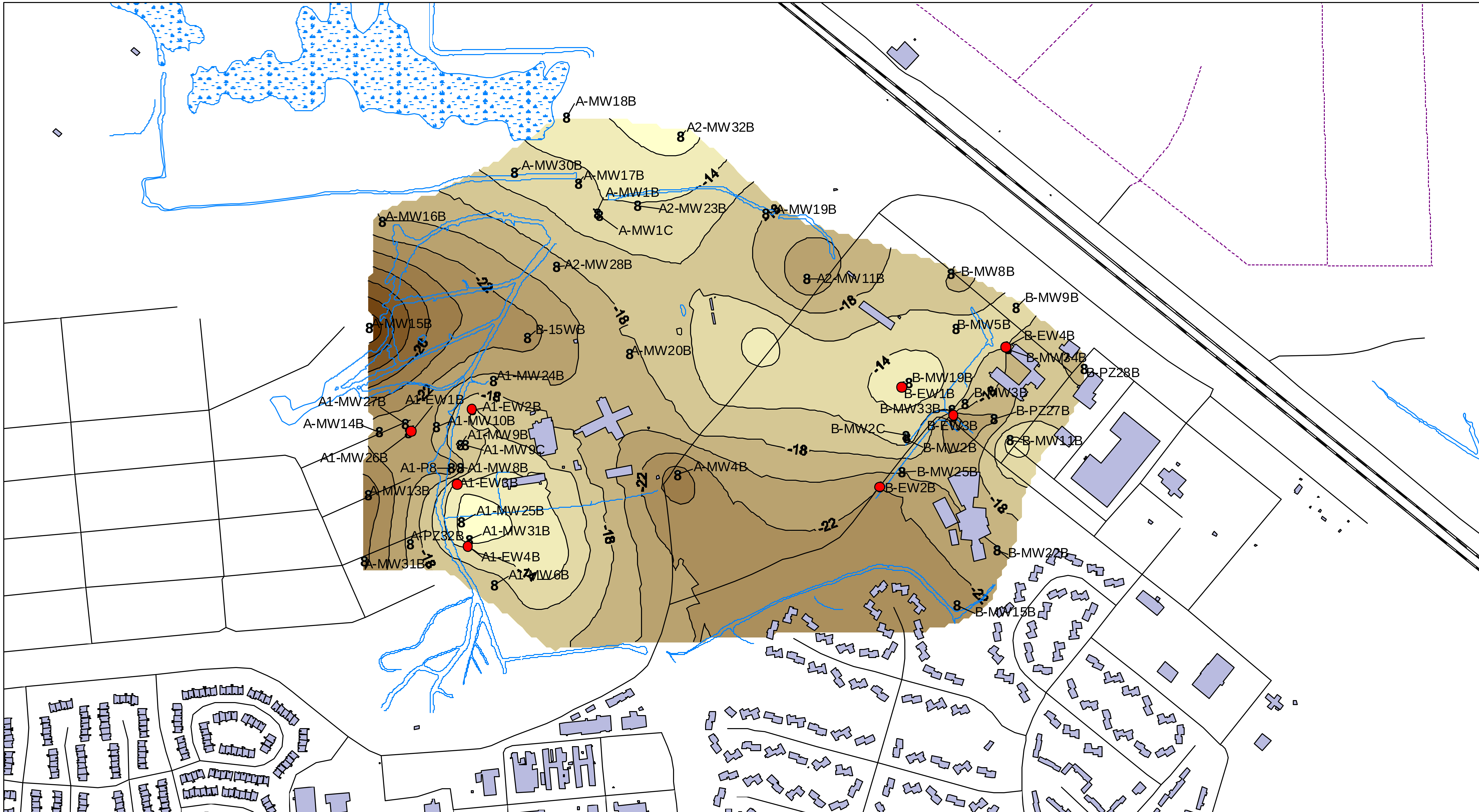
2.2 Hydrologic Setting

Camp Allen is located on a peninsula that is bordered on the north by Willoughby Bay, on the west by the Elizabeth River, and on the south by the Lafayette River. To the east of Camp Allen is a smaller water body, Mason Creek, that probably influences groundwater flow in the shallow Columbia aquifer.

Conceptually, groundwater flow in the shallow Columbia aquifer is typically under unconfined conditions, but can be locally confined in the presence of clay interbeds within the aquifer. Groundwater flow is derived mainly from distributed recharge at the ground surface. Recharge consists mainly of the infiltration of precipitation, which averages approximately 44 to 45 inches per year in the site vicinity. The rate at which precipitation infiltrates varies with soil type, topography, and land use. Urbanized areas, where much of the ground surface is covered by buildings and pavement, restricts the amount of infiltration and results in lower recharge rates. However, the rate of recharge in heavily vegetated areas will also be reduced by transpiration. Regionally, the distributed recharge to the water table results in groundwater mounding and an outward radial flow from the central area of the peninsula toward the water bodies on all four sides. Locally, groundwater discharges to various surface water features, including Bousch Creek, Masons Creek, Lafayette River, various un-named tributaries, and wetlands. Since the water table elevation is naturally higher than the potentiometric surface in the underlying Yorktown-Eastover aquifer, the shallow Columbia aquifer also discharges vertically into the deeper aquifer. However, groundwater pumping in the shallow aquifer could reverse the vertical flow.

Groundwater flow in the Yorktown-Eastover aquifer varies from confined or semi-confined to unconfined conditions, depending on the presence or absence of the Yorktown confining unit, and is driven mainly by regional influences, which include the major water bodies such as Chesapeake Bay and the Elizabeth and James Rivers. Direct recharge to the Yorktown-Eastover occurs far to the west where the unit crops out near the Fall Line. However, it is also recharged slowly by vertical leakage through its confining unit in areas where the shallow Columbia aquifer has higher potentiometric levels. The Yorktown-Eastover aquifer also has hydraulic communication with deeper coastal plain aquifers, but their influence is greatly reduced in the Camp Allen area by the relatively thick sequence of confining units that separates the Yorktown-Eastover from the underlying Chickahominy-Piney Point aquifer.

File Path: c:\18gis\nsn\nsn-egisjt.apr



LEGEND

8 Monitoring Well, Piezometer, or Soil Boring
Extraction Well
Shoreline
Runway
Taxiway
Arterial
Alley
Collector
Interstate
Local Road
Ramp
Buildings

Estimated Bottom Elevation

-12
-14
-16
-18
-20
-22
-24
-26
-28
-30
-32
-34

Contour Interval = 2 feet

N

500 0 500 1000 Feet

Figure 2-1
Contour Map of Bottom Elevations for the Columbia Aquifer

Camp Allen Landfill Groundwater Modeling
Naval Station Norfolk

CH2MHILL

SECTION 3

Aquifer Properties

Estimates of aquifer properties for use in the model were based on aquifer pumping tests performed from March 28 through April 21, 2000, as well as available regional hydrogeologic information.

A total of nine pumping tests were conducted, five in the shallow Columbia aquifer and four in the deeper Yorktown-Eastover aquifer. Appendix A provides a detailed description of these pumping tests and the test data analyses. Of these nine tests, two of the five tests in the Columbia aquifer and all four in the Yorktown-Eastover aquifer resulted in observable drawdown and data adequate for analysis. Results of the analyses for both aquifers are summarized in Table 3-1.

TABLE 3-1
Summary of Aquifer Pumping Test Results
Camp Allen Landfill Groundwater Modeling, Naval Station Norfolk Norfolk, Virginia

	Aquifer Property			
Aquifer	**T (feet2/day)**	**S**	**K (feet/day)**	**K' (feet/day)**
Columbia	**Area A**			
Range		--not available--		--
Average		--not available--		--
	Area B			
Range	1,058 - 1,307.1	4.56E-03 - 6.35E-2	43.9 - 55.6	--
Average	1,182.6	3.40E-02	49.8	--
Yorktown-Eastover	**Area A**			
Range	2,005.6 - 3,017.8	1.67E-04 - 6.37E-04	23.3 - 38.6	0.015 - 0.11
Average	2,329.2	3.04E-04	28.6	0.05
	Area B			
Range	856.7 - 1,105.6	1.64E-03 - 1.75E-03	9.1 - 12.2	6.43E-20 - 0.0042
Average	981.2	1.70E-03	10.6	0.0021

T: Transmissivity
S: Storativity
K: Aquifer hydraulic conductivity
K': Semi-confining unit hydraulic conductivity

3.1 Columbia Aquifer

Horizontal hydraulic conductivity values for the Columbia aquifer ranged from 43.9 to 55.6 feet/day and averaged 49.8 feet/day for Area B wells from the aquifer pumping test analyses. Transmissivity values obtained by fitting the confined Theis (1935) solution to the pumping test data (see Table 3-1 and Appendix A), together with the approximate saturated aquifer thickness at each location, were used to estimate the horizontal hydraulic conductivity values. The Theis solution provided the best fit to the drawdown data, of which only the compressive storage response was observed. These hydraulic conductivity values are comparable to those for a silty sand (Freeze and Cherry, 1979; Anderson and Woessner, 1992). However, the transmissivity values on which they are based are higher than the estimated 250 to 500 feet^2/day values given by Harsh and Laczniak (1990) for the site region. The fact that pumping in one of the test wells in Area B resulted in no observable drawdown in an observation well less than 20 feet away, and that two test wells were pumped dry early in the test, one in Area B and one in Area A, indicates that portions of the Columbia aquifer on-site are associated with hydraulic conductivity values significantly lower than those obtained from the pumping test analyses. This points to the degree of heterogeneity within the aquifer across the site. Due to the well pumping dry early in the test, no results were available for the Area A well.

No estimates of vertical hydraulic conductivity were available from either the aquifer pumping test analyses or available regional documentation. However, it was assumed that the ratio of horizontal to vertical hydraulic conductivity was at least 10:1 based on the presence of interlayered silty sands and clays noted in the boring logs. This leads to vertical hydraulic conductivity values of 4.4 to 5.6 feet/day based on the horizontal hydraulic conductivity values from the pumping test analyses.

Storativity values from the aquifer pumping test analyses, representing the initial release of groundwater from compressive storage, ranged from 4.56×10^{-3} to 6.35×10^{-2} and averaged 3.40×10^{-2}. These values are reasonable for a silty sand (Freeze and Cherry, 1979; Anderson and Woessner, 1992). No specific yield values were available from the pumping test analyses due to lack of observed gravity-yield response during the 24-hour pumping tests. However, Harsh and Laczniak (1990) cited a specific yield of 0.15 estimated from an analysis of an aquifer pumping test conducted on the Eastern Shore Peninsula of Virginia.

3.2 Yorktown-Eastover Aquifer

Transmissivity values for the Yorktown-Eastover aquifer ranged from 2,005.6 to 3,017.8 feet^2/day and averaged 2,329.2 feet^2/day for Area A wells from the aquifer pumping test analyses. For Area B wells, lower transmissivity values resulted, ranging from 856.7 to 1,105.6 feet^2/day and averaging 981.2 feet^2/day. The values were obtained by fitting the leaky Hantush-Jacob solution (Hantush and Jacob, 1955) to the pumping test data (see Table 3-1 and Appendix A). These transmissivity values compare well with the range of 200 to 3,000 feet^2/day cited by Harsh and Laczniak (1990) for the Yorktown-Eastover aquifer. Using the minimum aquifer thicknesses estimated from the on-site boring logs, horizontal hydraulic conductivity values of 23.3 to 38.6 feet/day in Area A and 9.1 to 12.2 feet/day in Area B were estimated from the transmissivity values (see Table 3-1). Using the total aquifer thickness of 206 feet estimated from the top-of-aquifer elevation and confining unit thickness maps by Meng and Harsh (1988), horizontal hydraulic conductivity values of 9.7 to 14.6 feet/day in Area A and 4.2 to 5.4 feet/day in Area B resulted from the transmissivity values. In either instance, the horizontal hydraulic conductivity values for the Yorktown-Eastover aquifer are less than those for the Columbia aquifer. Note that the extraction wells screen only 20 feet in the upper portion of the Yorktown-Eastover aquifer. Due to the interbedding of shelly sand beds with thin clay layers within the aquifer, it is possible that the drawdown response observed in the extraction wells reflects only the upper portions of the total aquifer thickness. Therefore, the horizontal hydraulic conductivity values may in fact be higher than those reported in Table 3-1.

No estimates of vertical hydraulic conductivity were available from the aquifer pumping test analyses. However, it was assumed that the ratio of horizontal to vertical hydraulic conductivity was at least 10:1 based on the presence of interlayered silty sands and clays noted in the boring logs. Thus, vertical hydraulic conductivity values of 0.91 to 3.9 feet/day were estimated from the horizontal hydraulic conductivity values listed in Table 3-1.

Storativity values from the aquifer pumping test analyses ranged from 1.67×10^{-4} to 6.37×10^{-4} and averaged 3.04×10^{-4} for Area A wells. For Area B wells, storativity values were higher, ranging from 1.64×10^{-3} to 1.75×10^{-3} and averaging 1.7×10^{-3}. These values are reasonable for confined aquifers with comparable materials (Freeze and Cherry, 1979; Anderson and Woessner, 1992; Fetter, 1994).

3.3 Yorktown Confining Unit

Analyses of the data for pumping tests in the Yorktown-Eastover aquifer provided vertical hydraulic conductivity values for the Yorktown confining unit. At Area A wells, vertical hydraulic conductivity values ranged from 0.015 to 0.11 feet/day and averaged 0.05 feet/day. At Area B wells, the vertical hydraulic conductivity values were lower, ranging from 6.4×10^{-20} to 0.0042 feet/day and averaging 0.0021 feet/day.

3.4 Aquifer Recharge

Harsh and Laczniak (1990) gave aquifier recharge at a rate of 15 inches/year to the water table for the coastal plain of Virginia, which encompasses the site region. This rate was estimated by removing the estimated rates of overland flow (6.5 inches/year) and evapotranspiration (21.5 inches/year assuming 50 percent loss of annual precipitation) from the average annual precipitation rate of approximately 43 inches/year. In the USGS

RASA groundwater model for the entire Virginia coastal plain, simulated aquifer recharge was calibrated to a rate of 3.2 inches / year (Meng and Harsh, 1988).

SECTION 4

Groundwater Model Development

4.1 Code Selection

The primary computer code used in the modeling was the U.S. Geological Survey's (USGS) modular groundwater modeling program known as MODFLOW (McDonald and Harbaugh, 1988). MODFLOW is a three-dimensional, finite-difference code that can simulate transient and steady-state flow in combinations of confined, unconfined, and semi-confined aquifers with a variety of boundary conditions and hydrologic stresses. The code has been in widespread use in the hydrogeologic profession since it was first introduced by the USGS in 1984. It has been thoroughly peer-reviewed and is considered highly reliable as a numerical solver of the basic equations of flow in saturated porous media.

4.2 Model Grid

The model grid consists of two layers, 157 rows, and 158 columns with variable horizontal grid spacing as shown in Figure 4-1. The use of variable horizontal grid spacing with finer discretization near the Camp Allen extraction system wells permitted better representation of simulated hydraulic heads near these features. Horizontal spacing ranges from a minimum of approximately 20 feet near extraction wells to a maximum of 300 feet near the margins of the model. The grid is rotated such that the columns are oriented at a 38.5-degree angle to the direction of north. In Figure 4-1, the active model cells are indicated by black grid lines and inactive cells are indicated by gray grid lines.

Due to the quasi-three-dimensional design of the model, model Layer 1 represents the shallow Columbia aquifer and model Layer 2 represents the deeper Yorktown-Eastover aquifer. The intervening Yorktown confining unit was not directly represented in the model by a model layer, but instead accounted for by the leakance term specifying the hydraulic connection between model Layers 1 and 2.

4.3 External Grid Boundaries

External boundary conditions in the model included prescribed heads and general head boundaries in Layers 1 and 2. These boundary conditions are shown in Figures 4-2 and 4-3. Prescribed heads in Layer 1 represent estimated stage levels of Willoughby Bay to the north, Masons Creek to the northeast, the Elizabeth River to the west, and the Lafayette River and associated inlets to the south. In Layer 2, the prescribed heads represent inflow / outflow within the Yorktown aquifer underlying these bodies of water. The

File Path: c:\18gis\nsn\camod_figures2.apr

Note: Basemap adapted from Norfolk North quadrangle of the USGS 7.5-minute series topographic maps.

LEGEND

Model Grid Boundary
Active Cells
Inactive Cells

N

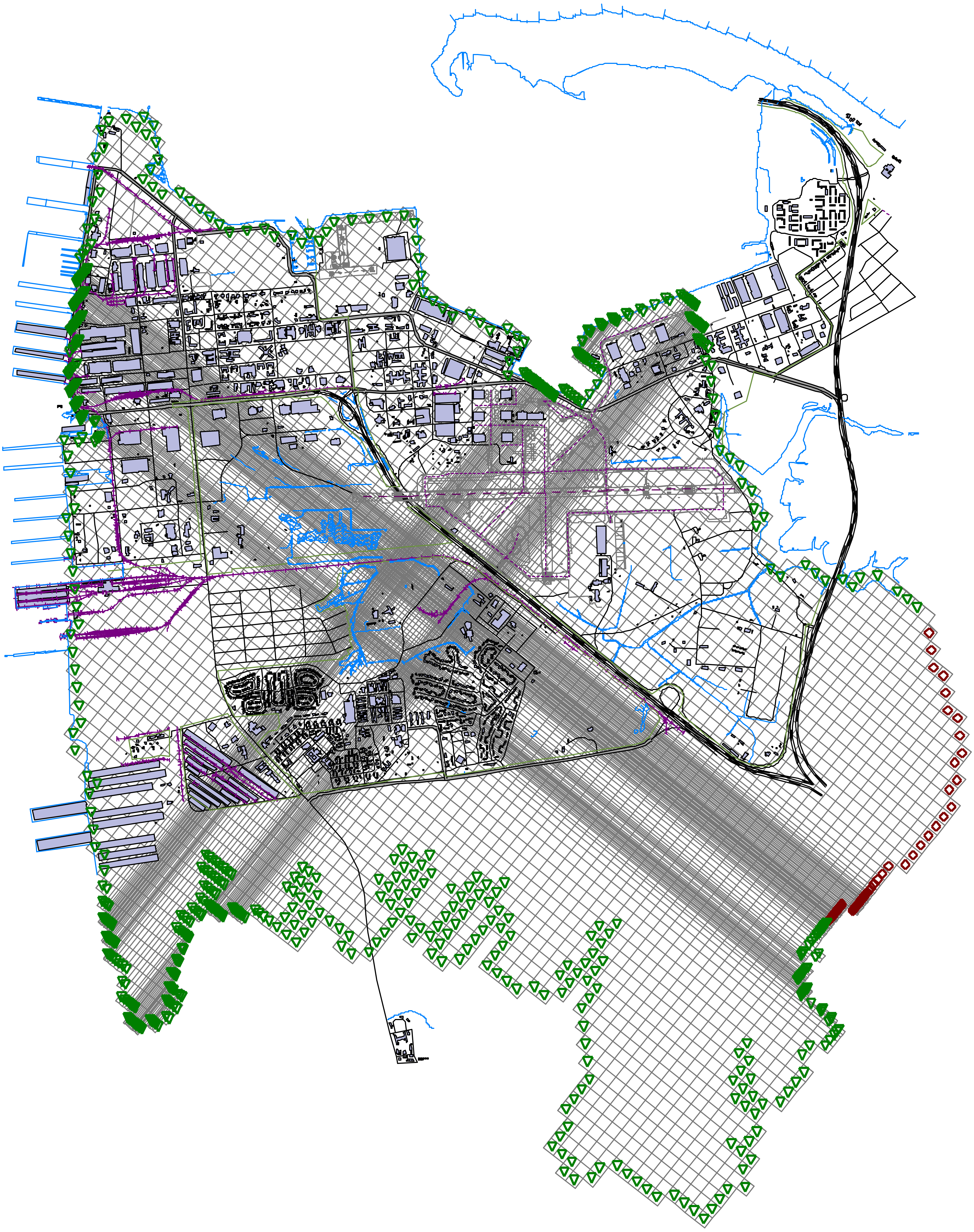
4000 0 4000 8000 Feet

Figure 4-1
Model Grid

Camp Allen Landfill Groundwater Modeling
Naval Station Norfolk

CH2MHILL

File Path: c:\18gis\nsn\camod_figures2.apr



LEGEND

- Constant Head Boundary
- General Head Boundary
- Active Cells
- Shoreline
- Runway
- Taxiway
- Airfields
- Property Lines
- Railroads
- Arterial
- Alley
- Collector
- Interstate
- Local Road
- Ramp
- Buildings

N

3000 0 3000 6000 Feet

Figure 4-2
External Boundary Conditions - Layer 1

Camp Allen Landfill Groundwater Modeling
Naval Station Norfolk

CH2MHILL

File Path: c:\18gis\nsn\camod_figures2.apr

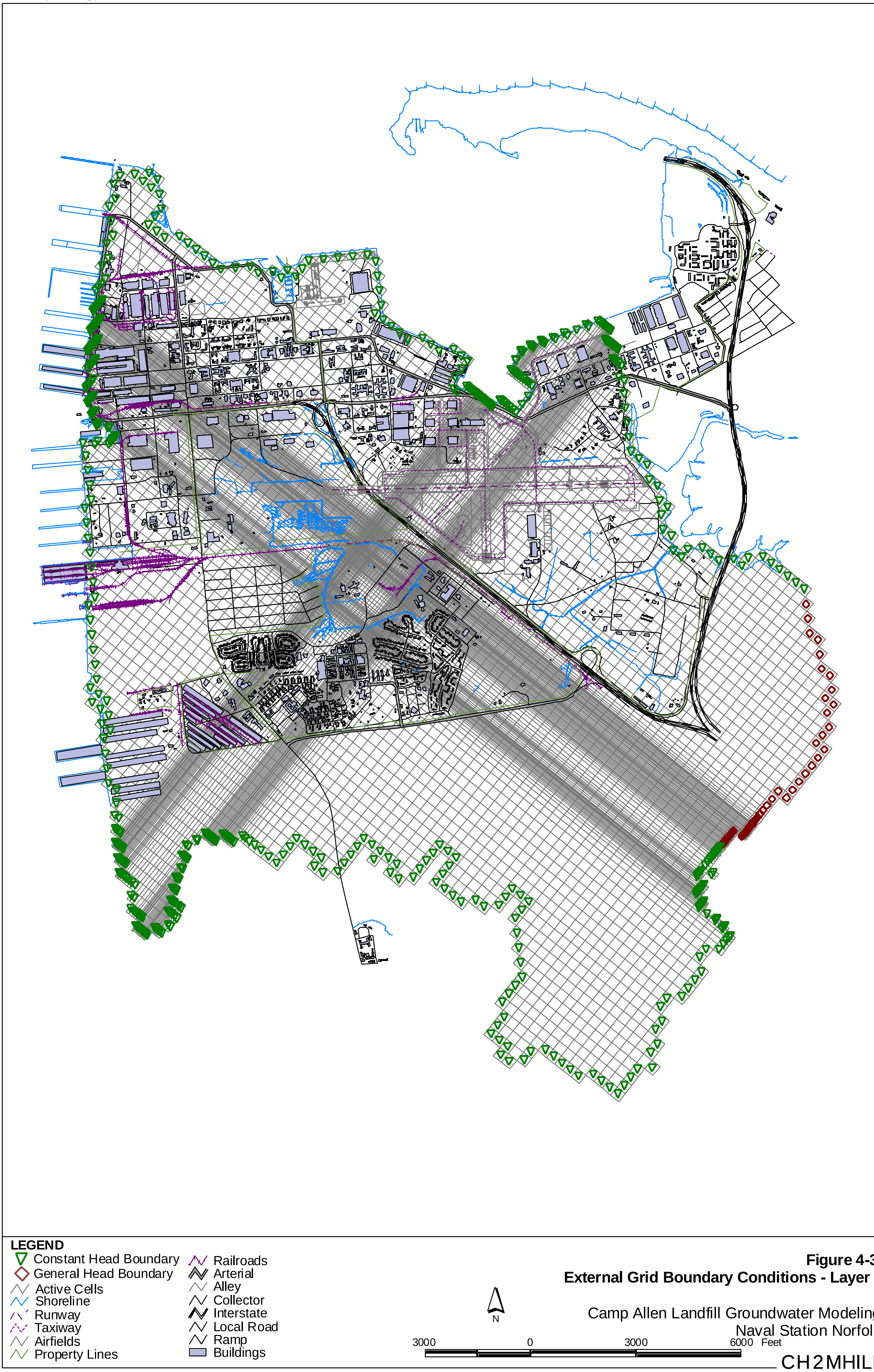


Figure 4-3
External Grid Boundary Conditions - Layer 2

Camp Allen Landfill Groundwater Modeling
Naval Station Norfolk

CH2MHILL

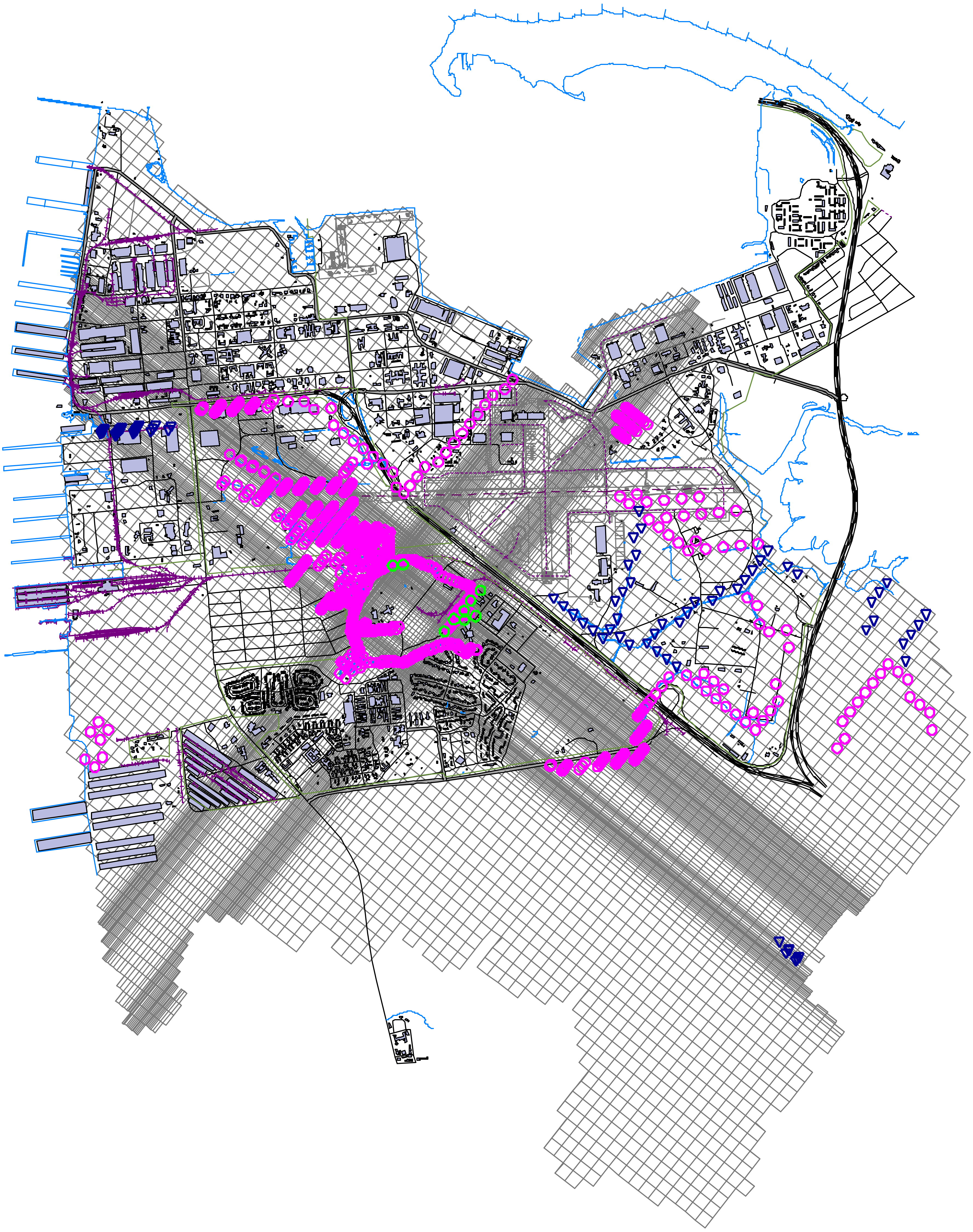
general head boundary conditions along the eastern margin in Layers 1 and 2 represent regional inflow / outflow between the peninsula and areas eastward within the Columbia and Yorktown-Eastover aquifers. With the general head boundary condition, flow is permitted through the boundary depending on the following: (1) the difference between the hydraulic head within the aquifer and that of a constant-head source specified at or beyond the boundary; and (2) the conductance of material separating the aquifer and the constant-head source. In this model, the groundwater elevations within the Columbia and Yorktown-Eastover aquifers continuing eastward were assumed to represent a constant-head source. Because the Columbia and Yorktown-Eastover aquifers represented the materials on either side of the boundary, the hydraulic conductivity and transmissivity values from the aquifer pumping test analyses were used in calculating the boundary conductance.

4.4 Internal Boundary Conditions

Internal boundary conditions in the model, as shown in Figures 4-4 and 4-5, included the following: (1) 17 pumping wells for the Camp Allen extraction system; (2) drains along Bousch Creek and other smaller intermittent to perennial streams and their tributaries; and (3) rivers along larger perennial streams. Of the 17 pumping wells, 9 are screened in the shallow Columbia aquifer and 8 are screened in the deeper Yorktown-Eastover aquifer (Figures 4-6 and 4-7).

Table 4-1 lists the average monthly pumping rates used in the model. These rates were estimated from Area A and Area B flow volumes obtained from flowmeters at the plant inlet for each area influent line and flow rates reported on the monthly well vault inspection forms for March 2000. The well vault flow rates were used to estimate the proportion of the area flow volume attributed to each extraction well. This was necessary because the wells were not individually metered. The proportion of area flow to each extraction well was then averaged over the 31 days in the month of March. For the shallow Area A wells, the following should be noted regarding the estimated pumping rates: the area flow volume used in estimating pumping rates included dual-phase vapor extraction; and February 2000 flow rates were used to approximate March 2000 rates because the flow rates reported at the time of the March 2000 well vault inspection were 0 gpm, despite the area flow volume being typical of that with the shallow Area A wells in operation.

File Path: c:\18gis\nsn\camod_figures2.apr



LEGEND

- Well
- River
- Drain
- Shoreline
- Runway
- Taxiway
- Airfields
- Property Lines
- Railroads
- Arterial
- Alley
- Collector
- Interstate
- Local Road
- Ramp
- Buildings
- Active Cells

N

3000 0 3000 6000 Feet

Figure 4-4
Internal Grid Boundary Conditions - Layer 1

Camp Allen Landfill Groundwater Modeling
Naval Station Norfolk

CH2MHILL

File Path: c:\18gis\nsn\camod_figures2.apr

LEGEND

- Well
- Shoreline
- Runway
- Taxiway
- Airfields
- Property Lines
- Railroads
- Arterial
- Alley
- Collector
- Interstate
- Local Road
- Ramp
- Buildings
- Active Cells

N

3000 0 3000 6000 Feet

Figure 4-5
Internal Grid Boundary Conditions - Layer 2

Camp Allen Landfill Groundwater Modeling
Naval Station Norfolk

CH2MHILL

File Path: c:\18gis\nsn\camod_figures2.apr

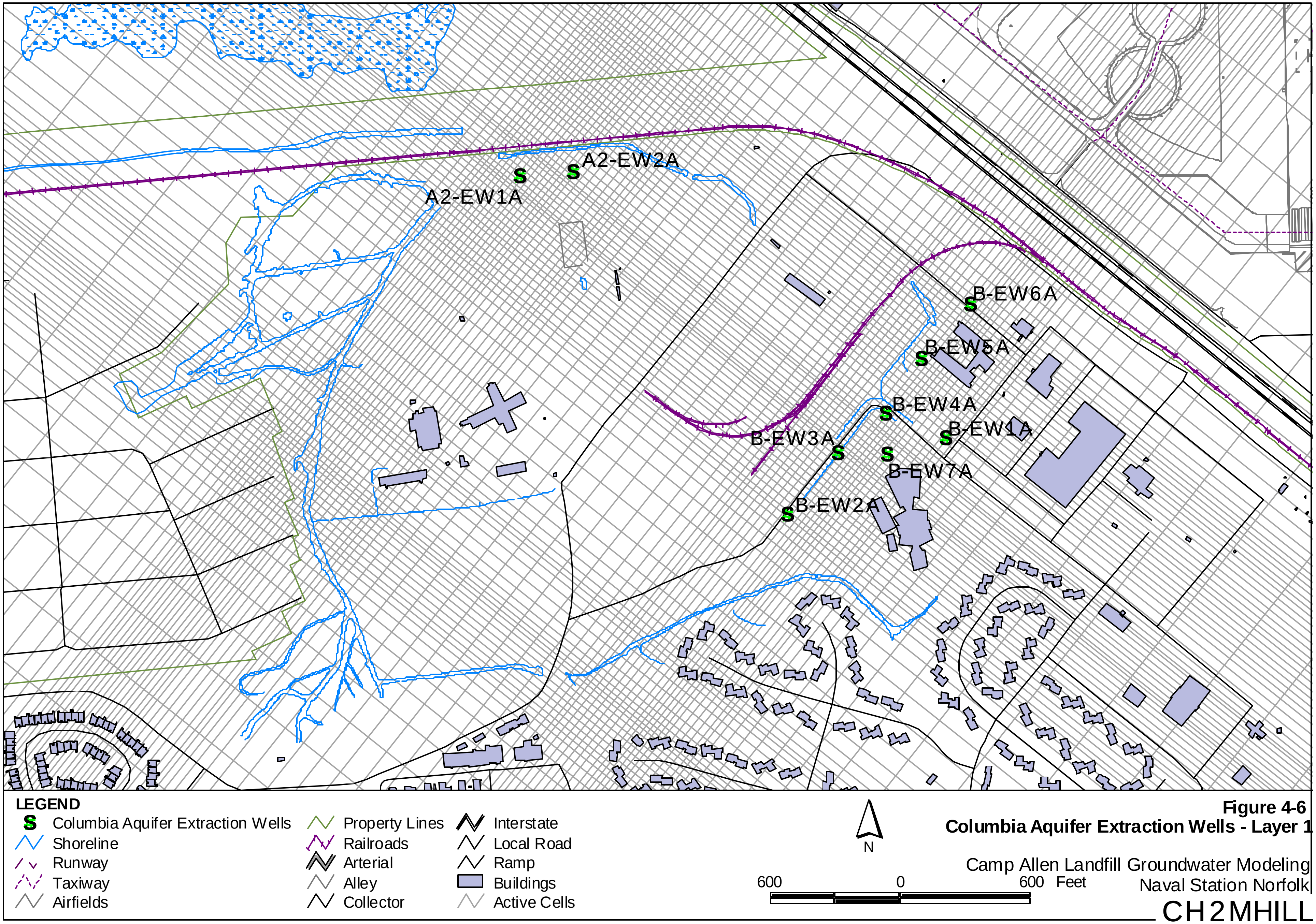


Figure 4-6
Columbia Aquifer Extraction Wells - Layer 1

Camp Allen Landfill Groundwater Modeling
Naval Station Norfolk

CH2MHILL

File Path: c:\18gis\nsn\camod_figures2.apr

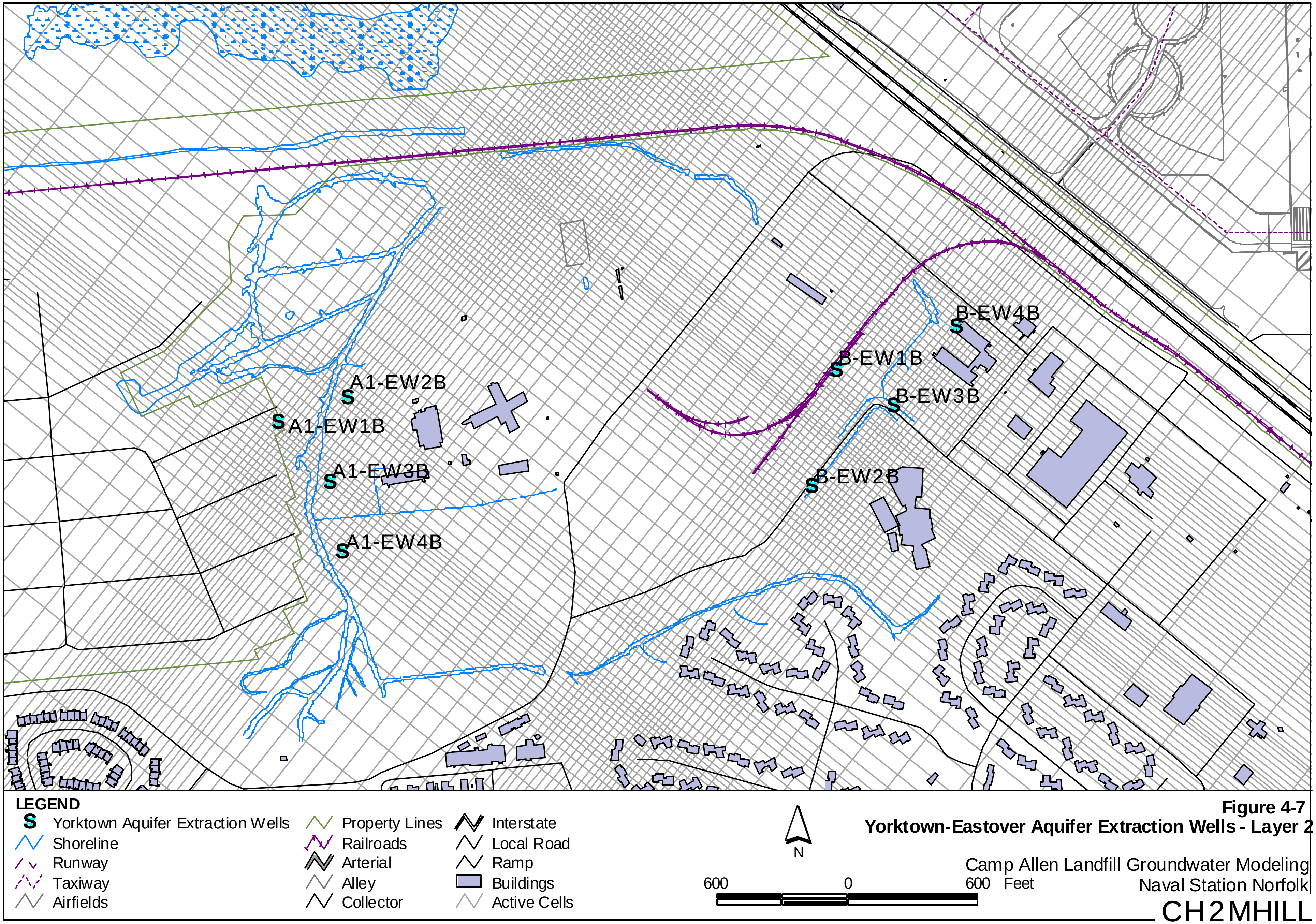


Figure 4-7
Yorktown-Eastover Aquifer Extraction Wells - Layer 2

Camp Allen Landfill Groundwater Modeling
Naval Station Norfolk

CH2MHILL

TABLE 4-1
Estimated Average Monthly Pumping Rates for Camp Allen Extraction Wells - March 2000
Camp Allen Landfill Groundwater Modeling, Naval Station Norfolk, Norfolk, Virginia

Aquifer	Well Vault ID	Well ID	Monthly Average Rate (feet^3/day)	Monthly Average Rate (gpm)	Aquifer	Well Vault ID	Well ID	Monthly Average Rate (feet^3/day)	Monthly Average Rate (gpm)
Columbia					**Yorktown-Eastover**				
Area A	201	A2EW-1A	199.0	1.0	**Area A**	--	A1-EW1B	0.0	0.0
	202	A2EW-2A	49.8	0.3		101	A1-EW2B	0.0	0.0
Area B	105D	B-EW1A	129.1	0.7		103	A1-EW3B	4,417.5	22.9
	105J	B-EW2A	284.0	1.5		106	A1-EW4B	5,448.3	28.3
	105H	B-EW3A	219.5	1.1	**Area B**	--	B-EW1B	0.0	0.0
	105E	B-EW4A	413.1	2.1		105I	B-EW2B	794.1	4.1
	105C	B-EW5A	206.5	1.1		105F	B-EW3B	794.1	4.1
	105A	B-EW6A	387.3	2.0		105B	B-EW4B	794.1	4.1
	105G	B-EW7A	413.1	2.1					

gpm: Gallons per minute

4.5 Initial Aquifer Parameter Zonation

Initial aquifer parameters assigned to the model layers were based on the recent aquifer pumping test results, as well as regional hydrogeologic information. These initial values were later modified during the calibration phase of the model development.

Model Layer 1, corresponding to the Columbia aquifer, was assigned unconfined flow conditions. An initial hydraulic conductivity value of 50 feet/day was assigned uniformly to Layer 1. This value falls within the 43.9 to 55.6 feet/day range determined from the shallow aquifer pumping test analyses discussed in Section 3.1 and Appendix A.

Model Layer 2, corresponding to the Yorktown-Eastover aquifer, was assigned confined flow conditions. Two initial transmissivity zones were assigned to Layer 2 with values of 1,000 and 2,000 feet^2/day, which stem from the difference in transmissivity values associated with Areas A and B. These transmissivity values fall within the 856.7 and 3,017.8 feet^2/day range determined from the deep aquifer pumping test analyses discussed in Section 3.2 and Appendix A. The boundary between these two zones was oriented north-south and was arbitrarily set to approximately the midpoint between the Area A and Area B extraction wells used in the aquifer pumping tests.

Leakance between Layers 1 and 2 was initially calculated using an interpolated thickness map of the Yorktown confining unit and a zonation map that incorporated calculated and assumed vertical hydraulic conductivity values for the confining unit and aquifers. This calculation also accounted for the presence or absence of the Yorktown confining unit as observed in boring logs. However, preliminary model runs indicated that holes in the Yorktown confining unit in certain areas did not necessarily correlate with simulated high leakage between the aquifers. Therefore, a more simplified approach was needed to better facilitate model calibration. Instead, uniform leakance of 2.24×10^{-4} day^{-1} was assigned, which was based in part on an assumed confining unit thickness of 20 feet for the entire modeling domain and on the 0.04477 feet / day vertical hydraulic conductivity for the confining unit averaged from the aquifer pumping test results.

Aquifer recharge at an initial rate of 3.2 inches / year was assigned uniformly to Layer 1 based on the calibrated regional USGS RASA model for the Virginia Coastal Plain.

SECTION 5

Groundwater Model Calibration

5.1 Calibration and Verification Targets

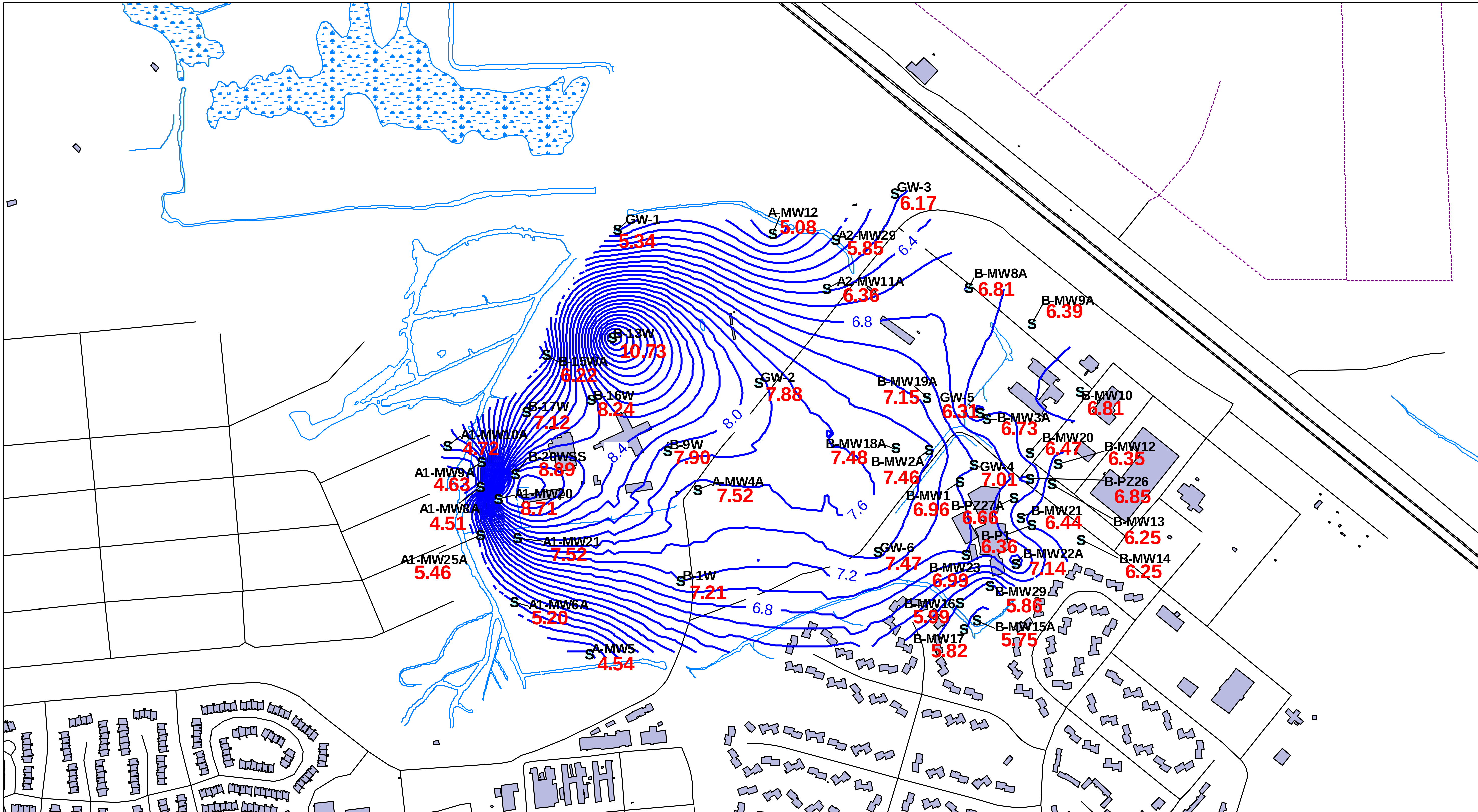
The groundwater flow model was calibrated to and verified with groundwater elevations measured at on-site monitoring wells and associated hydraulic gradients. Groundwater elevations measured during the July 1998 event served as calibration targets for the hydraulic head solution, representing ambient groundwater flow under non-pumping conditions. Groundwater elevations measured during the March 2000 event served as verification targets, representing groundwater flow with the extraction system in operation.

Figures 5-1 and 5-2 show contour maps of the July 1998 calibration target hydraulic heads for model Layers 1 and 2, associated with the shallow Columbia aquifer and the deeper Yorktown-Eastover aquifer, respectively. In the shallow Columbia (Layer 1), the contoured target heads indicate the presence of a groundwater high roughly centered over Area A of the Camp Allen Landfill. Groundwater flows radially outward in all directions from this area with relatively steep hydraulic gradients. These hydraulic gradients flatten to the east toward Area B, where groundwater flow directions range from southeast to northeast. In the deeper Yorktown-Eastover aquifer (Layer 2), the contoured target heads indicate the presence of the groundwater high roughly centered over Area B. Groundwater flows radially outward in all directions from this high. In Area A, groundwater flow directions are to the west with hydraulic gradients steeper than those associated with the groundwater high in Area B.

Directions of vertical flow under the ambient conditions indicated by the July 1998 target hydraulic heads are shown in Figure 5-3. As indicated by the green contour lines, vertical flow directions between the Columbia and Yorktown-Eastover aquifers are downward over the majority of the site. Near Bousch Creek and associated ditches, vertical flow directions are upward (red contour lines).

Figures 5-4 and 5-5 show contour maps of the March 2000 verification target hydraulic heads for model Layers 1 and 2. The contoured target heads indicate that the overall groundwater flow directions in the Columbia and Yorktown-Eastover aquifers in March 2000 generally mirrored the trends observed for the July 1998 target heads. In the shallow Columbia (Layer 1), the groundwater high centered over Area A persisted in the presence of pumping. While pumping in Area A appears to have had minimal effect on water levels measured in the nearest monitoring wells, pumping in Area B has resulted in flattened hydraulic gradients and evident capture zones. In the Yorktown-Eastover

File Path: c:\18gis\nsn\nsn-egisjt.apr



LEGEND

- Monitoring Well, Piezometer, or Soil Boring
- Shoreline
- Runway
- Taxiway
- Arterial
- Alley
- Collector
- Interstate
- Local Road
- Ramp
- Buildings
- Estimated Groundwater Elevation

Contour Interval = 0.2 feet

N

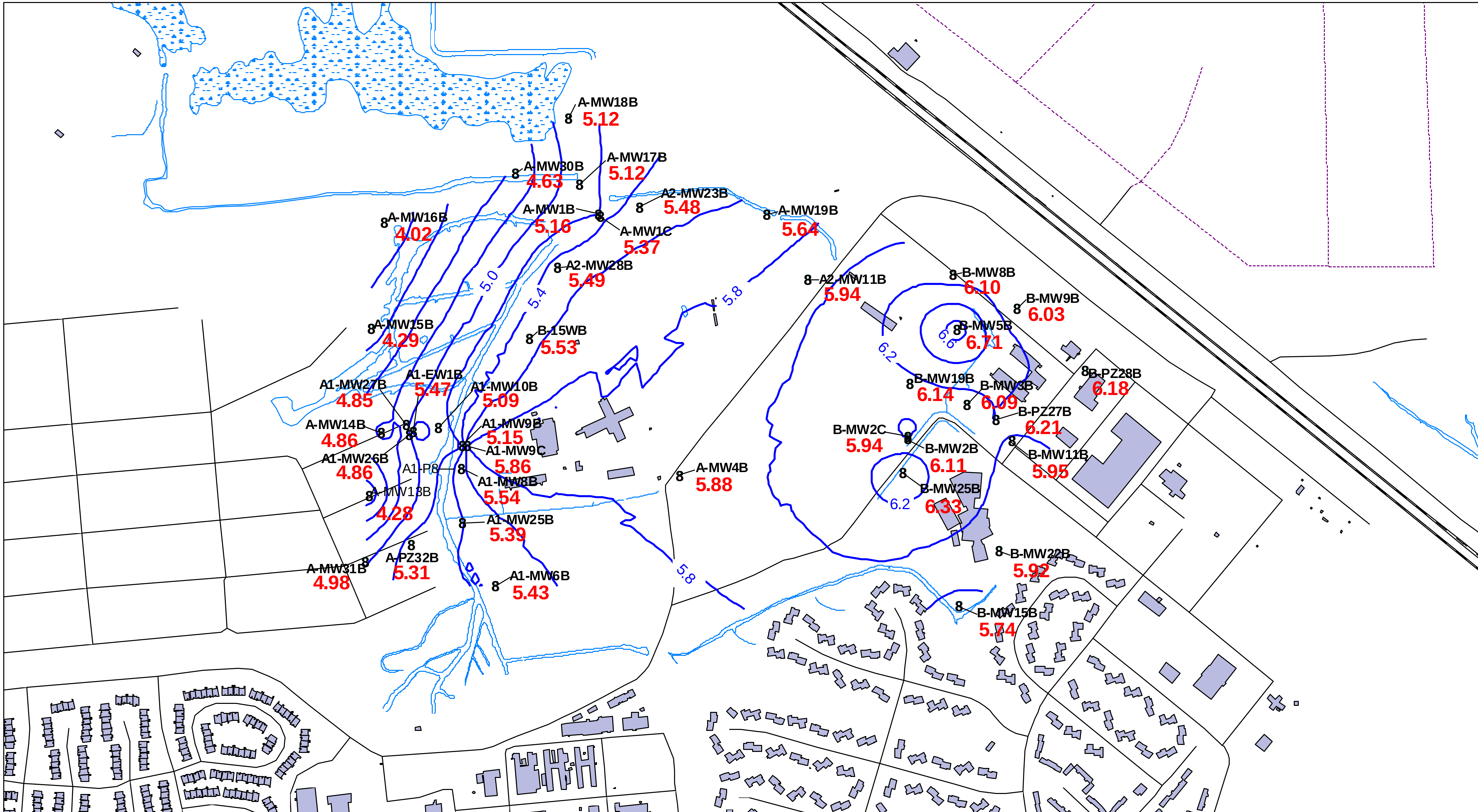
500 0 500 1000 Feet

Figure 5-1
July 1998 Non-pumping Calibration Target
Hydraulic Heads – Layer 1

Camp Allen Landfill Groundwater Modeling
Naval Station Norfolk

CH2MHILL

File Path: c:\18gis\nsn\nsn-egisjt.apr



LEGEND

8 Monitoring Well, Piezometer, or Soil Boring
Shoreline
Runway
Taxiway
Arterial
Alley
Collector
Interstate
Local Road
Ramp
Buildings
Estimated Groundwater Elevation

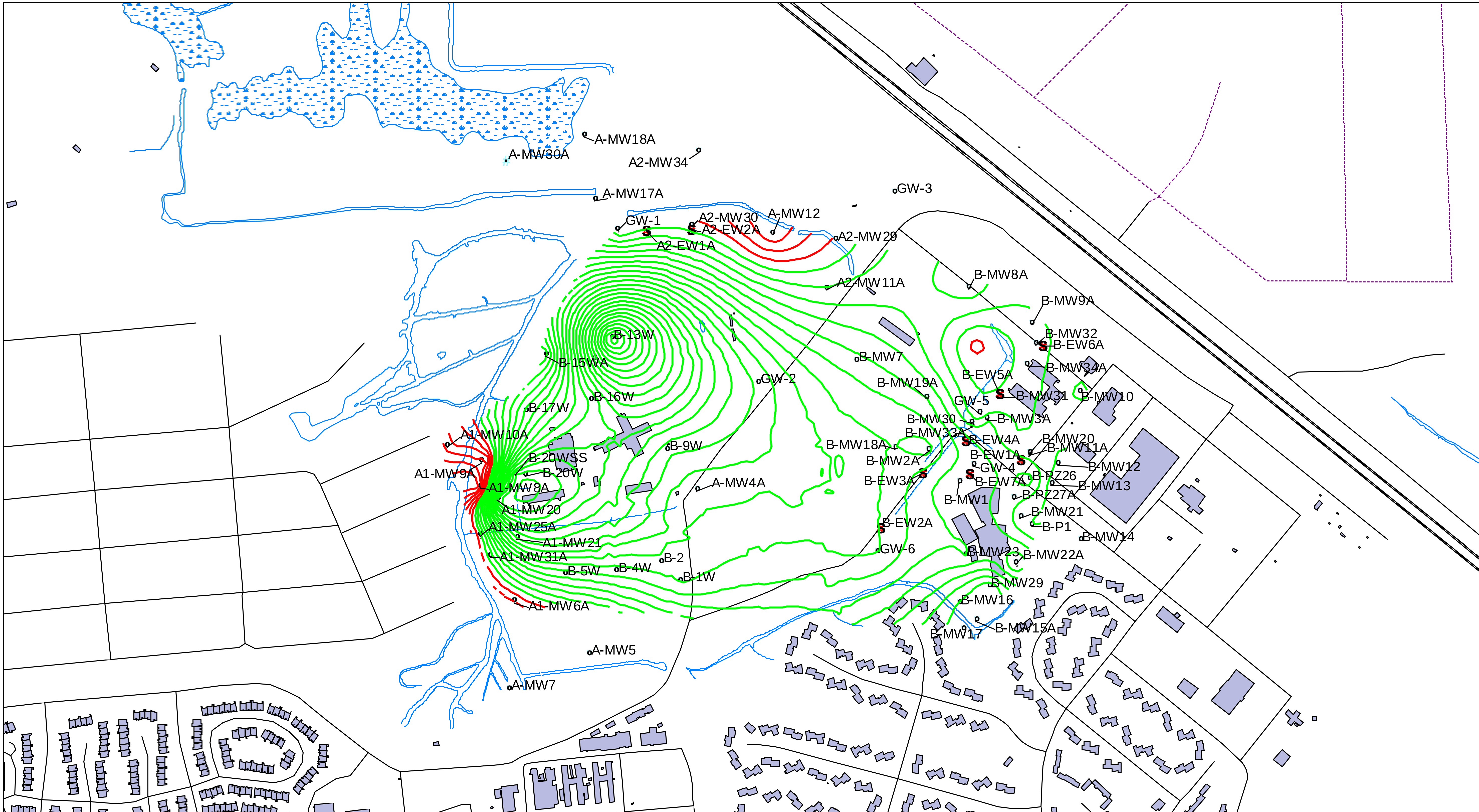
Contour Interval = 0.2 feet

Figure 5-2
July 1998 Non-pumping Calibration Target
Hydraulic Heads – Layer 2

Camp Allen Landfill Groundwater Modeling
Naval Station Norfolk

CH2MHILL

File Path: c:\18gis\nsn\nsn-egisjt.apr



LEGEND

- Monitoring Well, Piezometer, or Soil Boring
- Shoreline
- Runway
- Taxiway
- Arterial
- Alley
- Collector
- Interstate
- Local Road
- Ramp
- Buildings

Direction of Vertical Gradient

- Downward
- Upward

Contour Interval = 0.2 feet

N

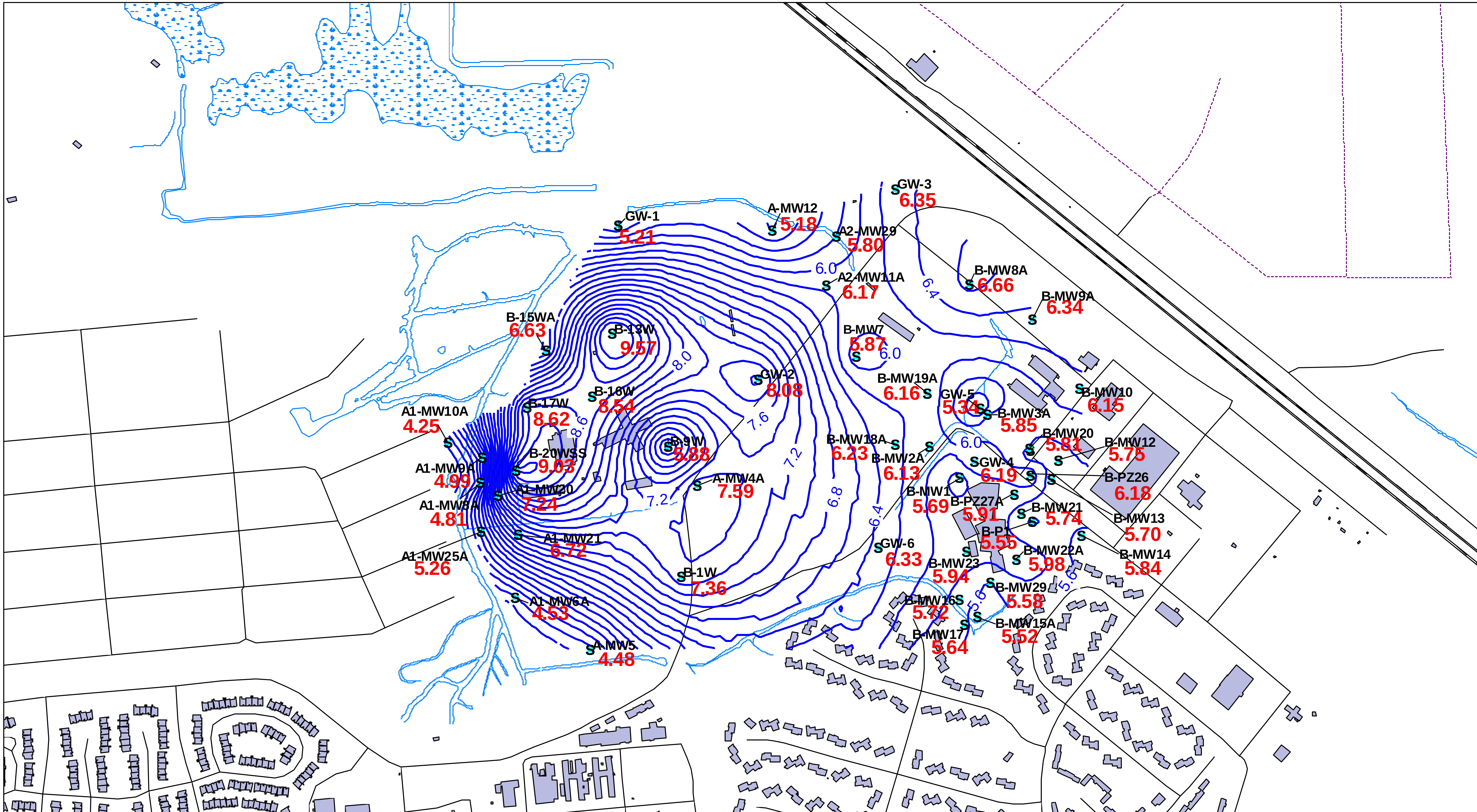
500 0 500 1000 Feet

Figure 5-3
July 1998 Directions of Vertical Flow

Camp Allen Landfill Groundwater Modeling
Naval Station Norfolk

CH2MHILL

File Path: c:\18gis\nsn\nsn-egisjt.apr



LEGEND

- Monitoring Well, Piezometer, or Soil Boring
- Shoreline
- Runway
- Taxiway
- Arterial
- Alley
- Collector
- Interstate
- Local Road
- Ramp
- Buildings
- Estimated Groundwater Elevation

Contour Interval = 0.2 feet

N

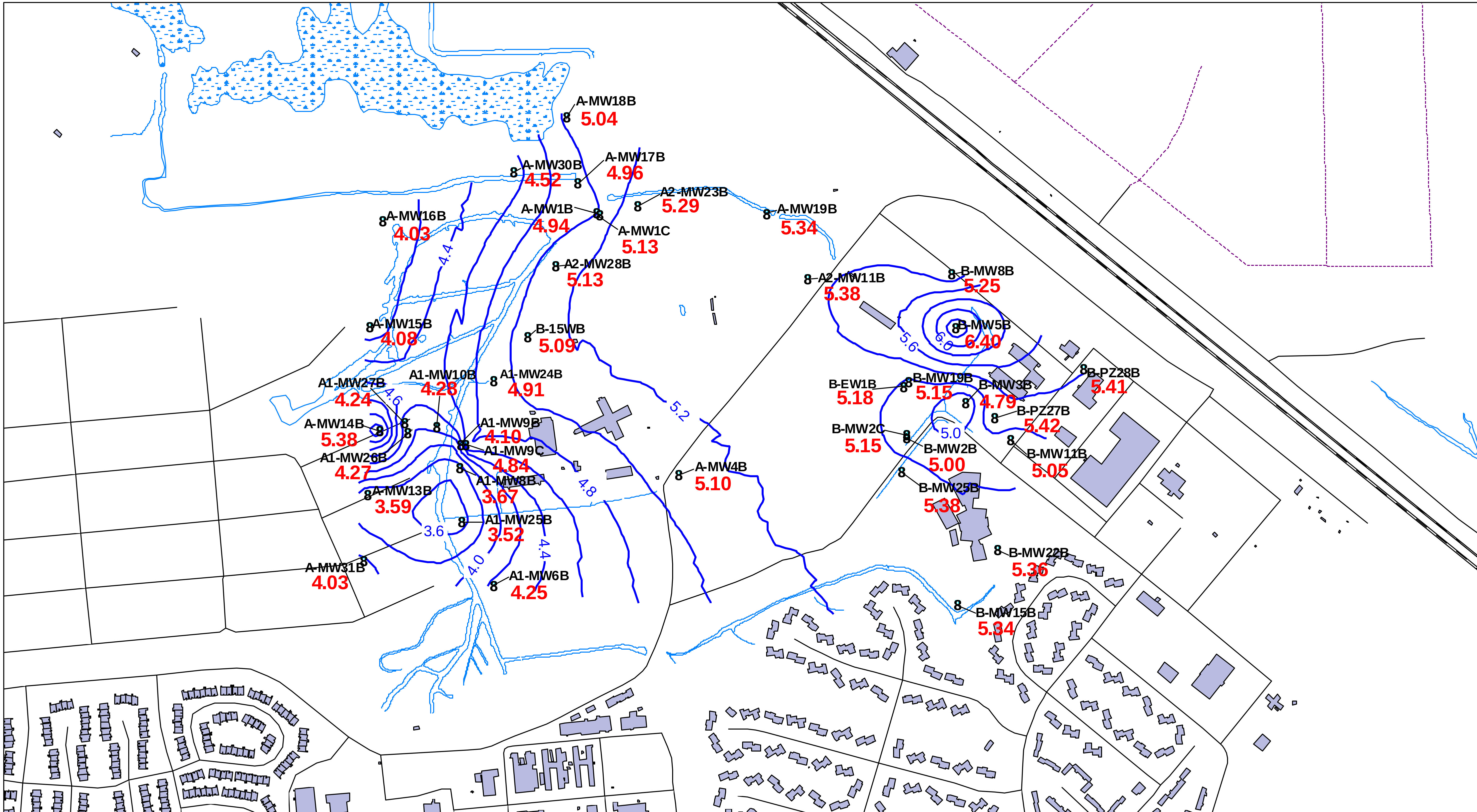
500 0 500 1000 Feet

Figure 5-4
March 2000 Pumping Verification Target Hydraulic Heads - Layer 1

Camp Allen Landfill Groundwater Modeling
Naval Station Norfolk

CH2MHILL

File Path: c:\18gis\nsn\nsn-egisjt.apr



LEGEND
8 Monitoring Well, Piezometer, or Soil Boring
Shoreline
Runway
Taxiway
Arterial
Alley
Collector
Interstate
Local Road
Ramp
Buildings

N

500 0 500 1000 Feet

Figure 5-5
March 2000 Pumping Verification Target Hydraulic Heads - Layer 2

Camp Allen Landfill Groundwater Modeling
Naval Station Norfolk

CH2MHILL

aquifer (Layer 2), pumping in both Areas A and B has resulted in capture zones of greater lateral extent than those observed in the shallow Columbia aquifer in Area B.

5.2 Calibration, Verification, and Simulated Aquifer Parameters

Calibrating the model to July 1998 (non-pumping) groundwater flow conditions required various modifications to the initial model. The simulation of the groundwater high observed in the Columbia aquifer in Area A required zones of lower hydraulic conductivity (red, orange, purple, and green) shown in Figure 5-6 and lower vertical leakance (red) shown in Figure 5-7, as well as higher recharge shown in Figure 5-8. A review of the boring logs indicated the presence of greater thicknesses of clay interbeds within the shallow Columbia aquifer in Area A, which supports the use of lower hydraulic conductivity and vertical leakance zones. Also, much of Area A is covered by fields with limited vegetation, and the landfill is covered by fill and native soil rather than a cap designed to reduce infiltration. These conditions can contribute to higher rates of infiltration, and thus higher aquifer recharge.

To simulate the groundwater high in the Yorktown-Eastover aquifer in Area B, a zone of higher leakance (light blue) was required as shown in Figure 5-7. This zone of higher leakance correlates with locations where the Yorktown confining unit is known to be absent, thus permitting greater hydraulic communication between the shallow Columbia and deeper Yorktown-Eastover aquifers.

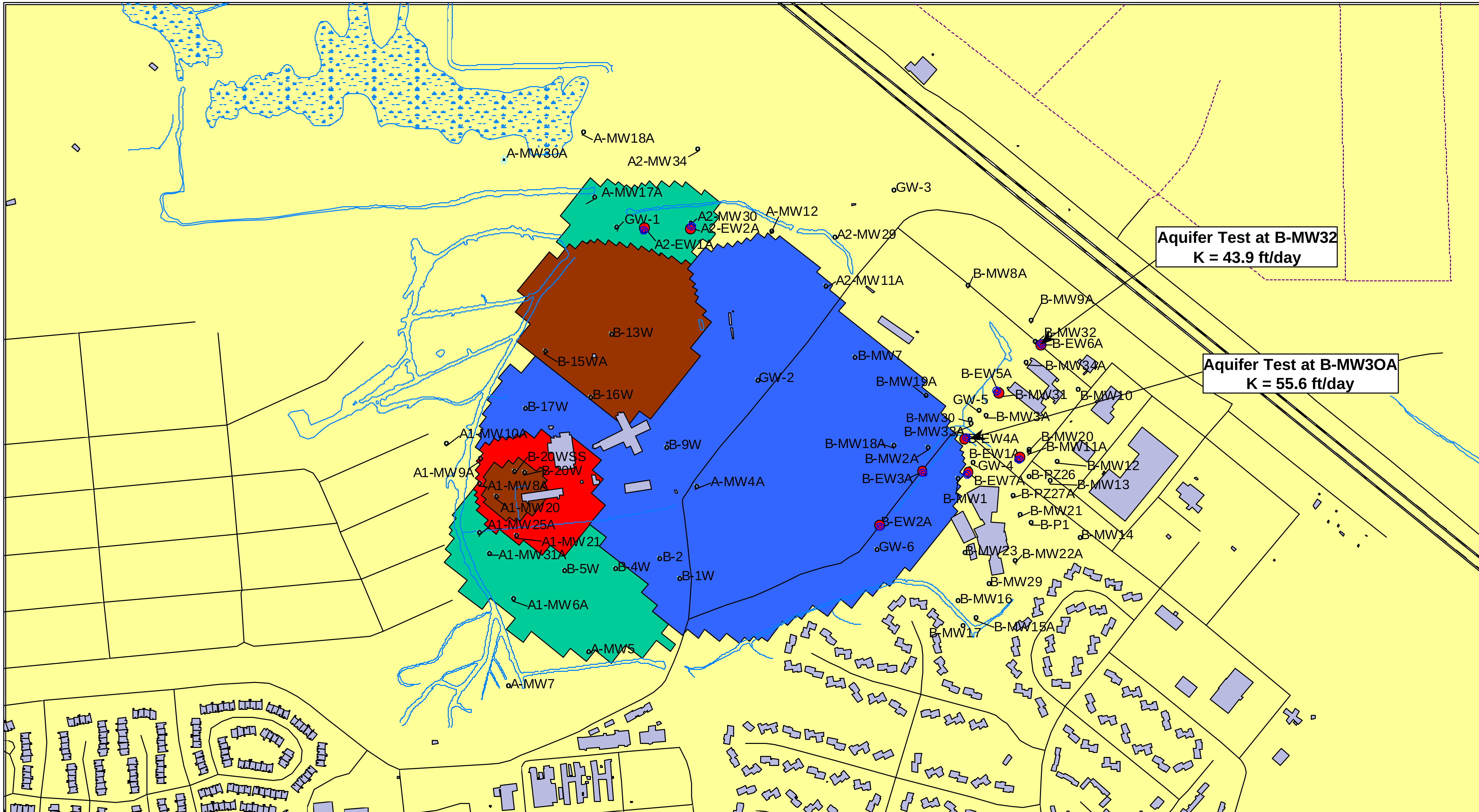
Simulating the steep hydraulic gradients noted in the Yorktown-Eastover aquifer on the west side of Area A required a zone of lower transmissivity (red) shown in Figure 5-9. Although no aquifer pumping tests have been conducted to confirm or deny the presence of lower transmissivity materials within the Yorktown-Eastover aquifer on the west side of Bousch Creek, historical water level observations indicate that steeper hydraulic gradients in this area persist over time.

Verification of the groundwater model to March 2000 (pumping) groundwater flow conditions revealed the need for additional zones of higher leakance (green) shown in Figure 5-7. These higher leakance zones also correspond to locations where the Yorktown confining unit is known to be absent. This suggests the importance of the effects of pumping in the Yorktown-Eastover aquifer on water levels in the overlying Columbia aquifer, especially where the confining unit is absent.

5.3 Calibration and Verification Results

Residuals, the differences between the target hydraulic heads and the simulated hydraulic heads at the target locations, were used to assess the level of model calibration and to determine the model verification. Table 5-1 lists the residual statistics for the calibration and verification. Mean error is a measure of the overall model bias, while the root mean square is a measure of how well the model mimics gradients and water levels at specific

File Path: c:\18gis\nsn\nsn-egisjt.apr



LEGEND

- Monitoring Well, Piezometer, or Soil Boring
- Extraction Well
- Shoreline
- Runway
- Taxiway
- Arterial
- Alley
- Collector
- Interstate
- Local Road
- Ramp
- Buildings

Hydraulic Conductivity Values

- 50 ft/day
- 20 ft/day
- 10 ft/day
- 5 ft/day
- 1 ft/day

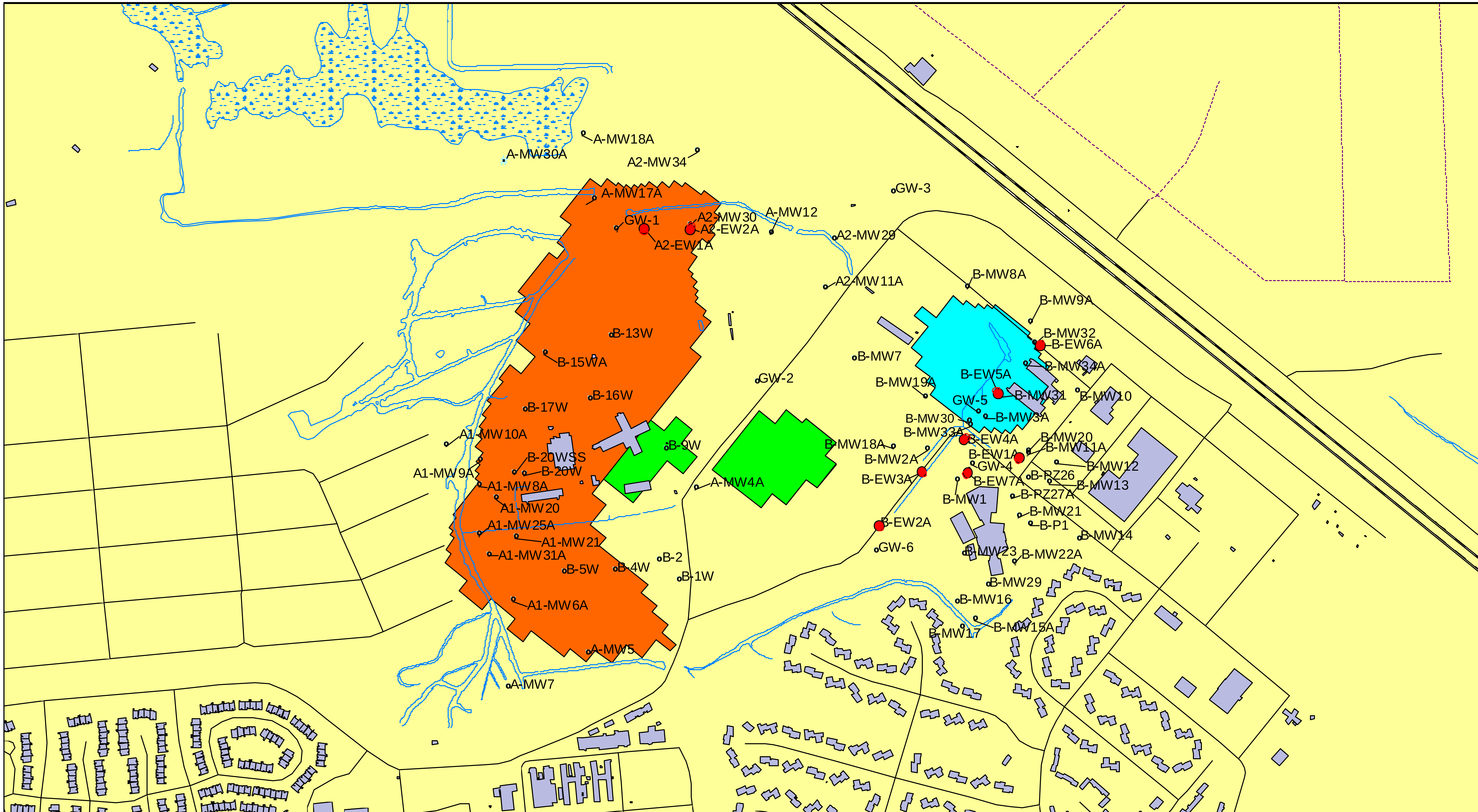
N

500 0 500 1000 Feet

Figure 5-6
Calibrated Hydraulic Conductivity Zonation Map – Layer 1

Camp Allen Landfill Groundwater Modeling
Naval Station Norfolk

CH2MHILL



LEGEND

- Monitoring Well, Piezometer, or Soil Boring
- Extraction Well
- Shoreline
- Runway
- Taxiway
- Arterial
- Alley
- Collector
- Interstate
- Local Road
- Ramp
- Buildings

Leakance Zonation

- 2.24×10^{-2} per day
- 2.24×10^{-3} per day
- 7.24×10^{-4} per day
- 2.24×10^{-4} per day

N

500 0 500 1000 Feet

Figure 5-7
Calibrated Vertical Conductance Zonation Map

Camp Allen Landfill Groundwater Modeling
Naval Station Norfolk

CH2MHILL

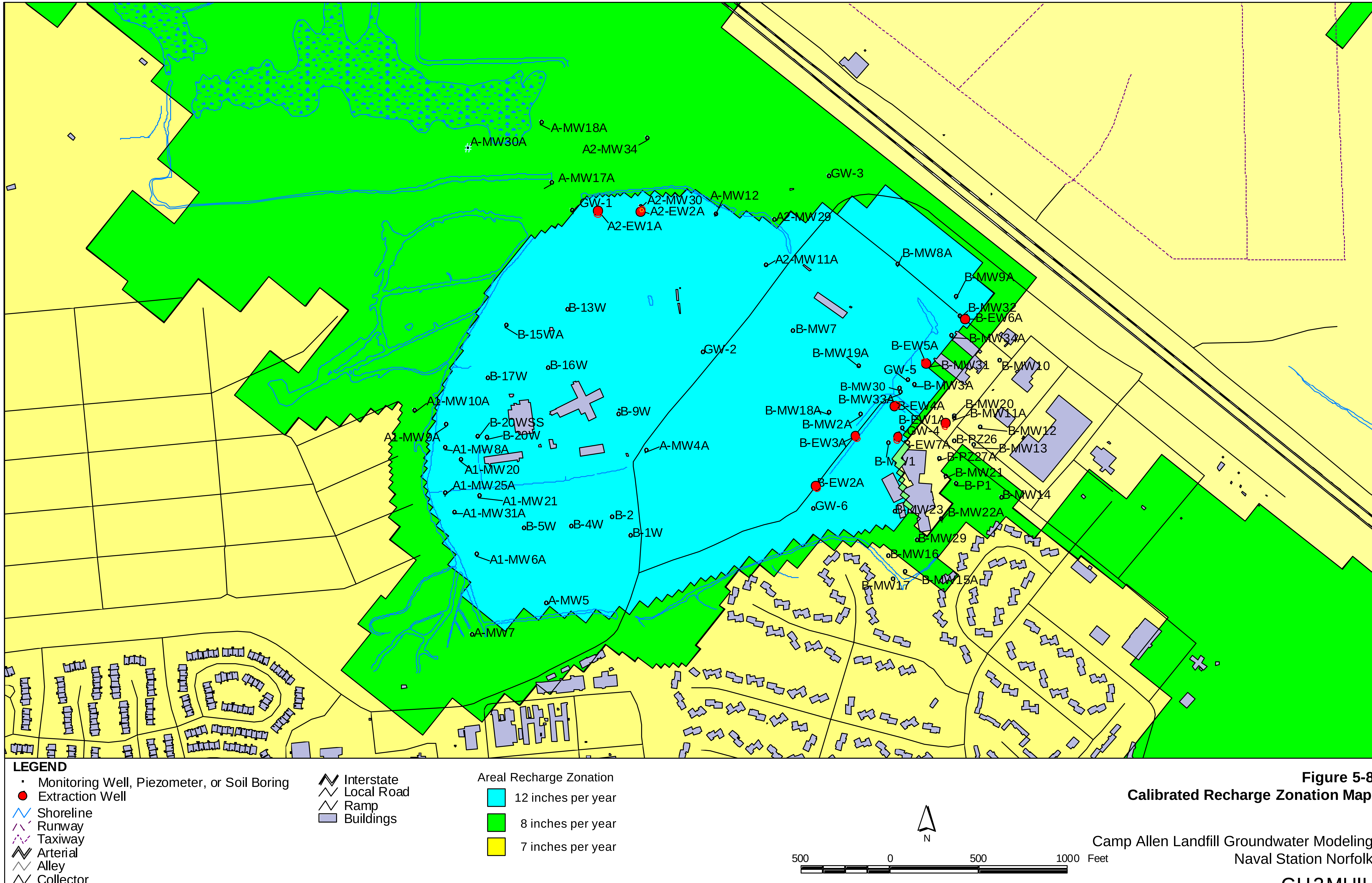
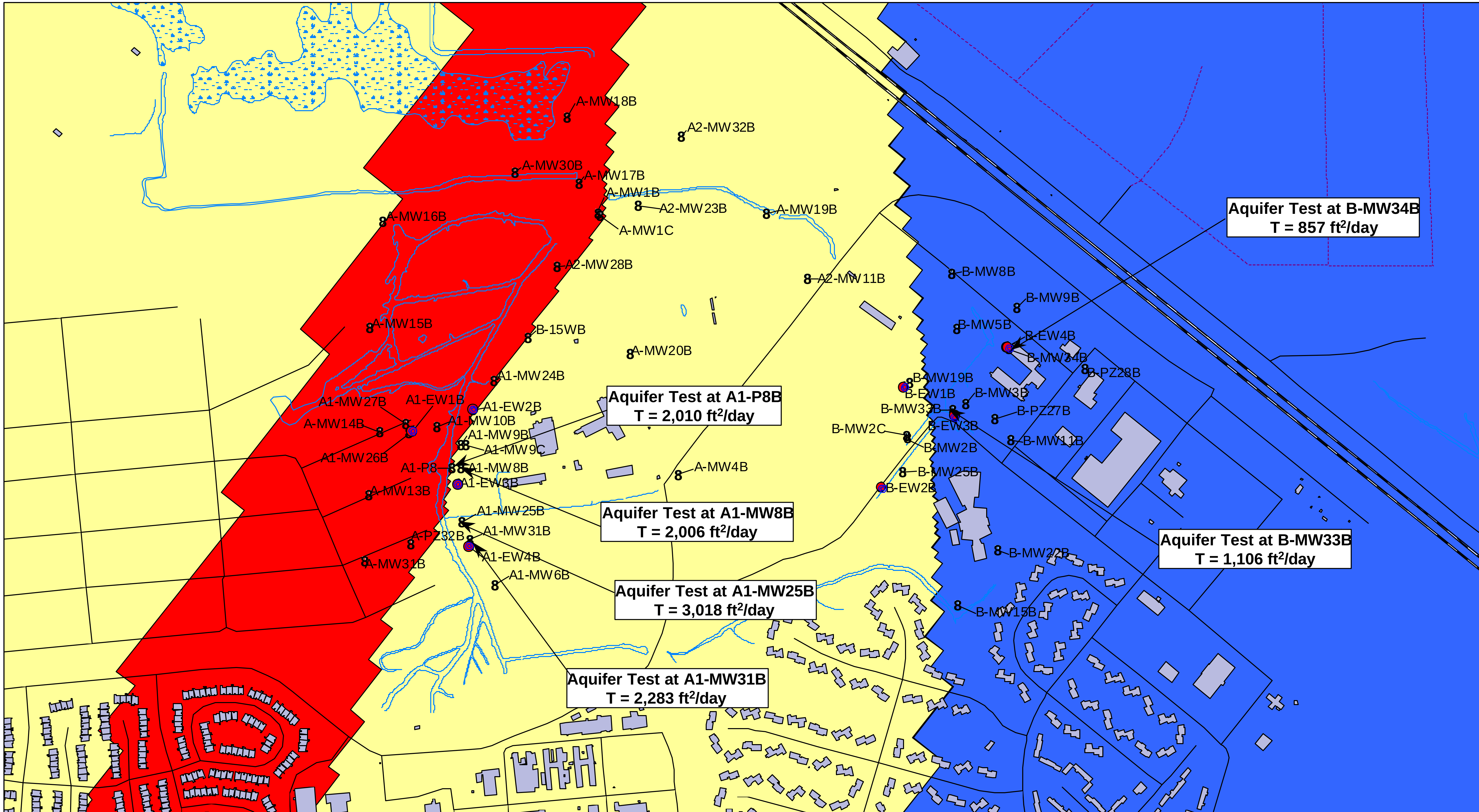


Figure 5-8
Calibrated Recharge Zonation Map

Camp Allen Landfill Groundwater Modeling
Naval Station Norfolk

CH2MHILL

File Path: c:\18gis\nsn\nsn-egisjt.apr



LEGEND

- 8 Monitoring Well, Piezometer, or Soil Boring
- Extraction Well
- Shoreline
- Runway
- Taxiway
- Arterial
- Alley
- Collector
- Interstate
- Local Road
- Ramp
- Buildings

Transmissivity Values

- 2,000 ft²/day
- 1,000 ft²/day
- 50 ft²/day

N

500 0 500 1000 Feet

Figure 5-9
Calibrated Transmissivity Zonation Map – Layer 2

Camp Allen Landfill Groundwater Modeling
Naval Station Norfolk

CH2MHILL

locations. Both the mean error and root mean square of the residuals were less than 1 foot in either model layer for both the calibration and verification simulations.

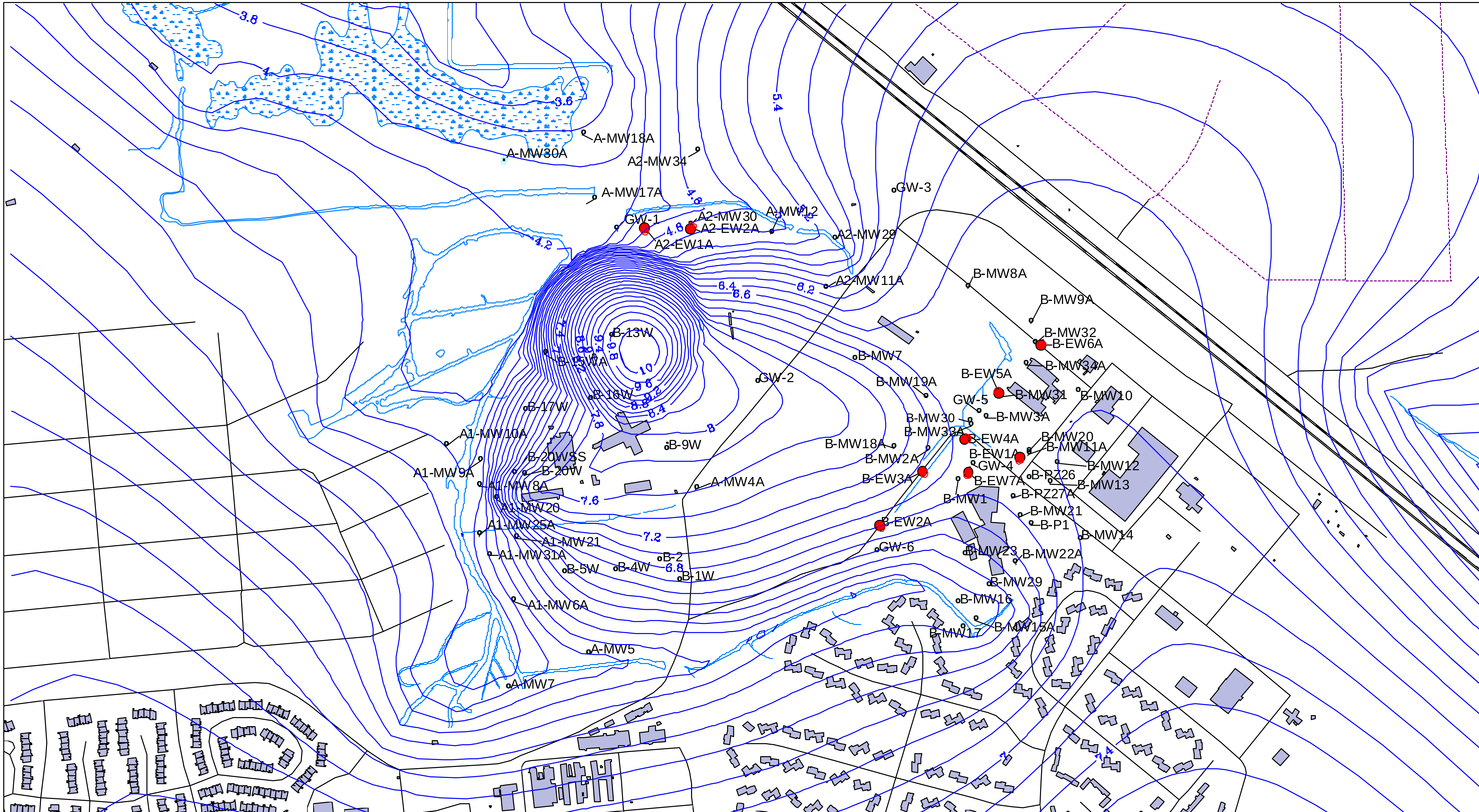
TABLE 5-1
Residual Statistics for Calibration and Verification Simulations
Camp Allen Landfill Groundwater Modeling, Naval Station Norfolk, Norfolk, Virginia

		Layer 1 Columbia Aquifer	Layer 2 Yorktown Aquifer
Calibration	Mean Error	-0.31	0.37
	Root Mean Square	0.76	0.49
Verification	Mean Error	-0.35	-0.24
	Root Mean Square	0.73	0.66

Contour maps of simulated calibration hydraulic heads are shown in Figures 5-10 and 5-11 for Layers 1 and 2, respectively. These simulated hydraulic heads and gradients compare well with the target heads and gradients shown in Figures 5-1 and 5-2. The simulated directions of vertical flow shown in Figure 5-12, indicated by the difference between simulated heads in Layers 1 and 2, also compare well with those determined from measured groundwater elevations shown in Figure 5-3. In general, vertical flow is downward in the presence of the groundwater high within the shallow Columbia aquifer in Area A and extending toward Area B. Vertical flow reverses to upward in proximity to Bousch Creek, related drainage ditches, and other surface water bodies.

Contour maps of the simulated verification hydraulic heads are shown in Figures 5-13 and 5-14. While the simulated heads in Layer 1 compare relatively well with the measured verification target heads depicted in Figure 5-4, differences exist between the simulated and measured heads (see Figure 5-5) for Layer 2. Primarily, the simulated pumping cones of depression surrounding extraction wells A1-EW3B and A1-EW4B in Area A are deeper and laterally more extensive than those indicated by the measured water levels. This may need to be addressed in the future as more data regarding aquifer properties and pumping rates becomes available.

File Path: c:\18gis\nsn\nsn-egisjt.apr



LEGEND

- Monitoring Well, Piezometer, or Soil Boring
- Extraction Well
- Shoreline
- Runway
- Taxiway
- Arterial
- Alley
- Collector
- Interstate
- Local Road
- Ramp
- Buildings
- Simulated Groundwater Elevation

Contour Interval = 0.2 feet

N

500 0 500 1000 Feet

Figure 5-10

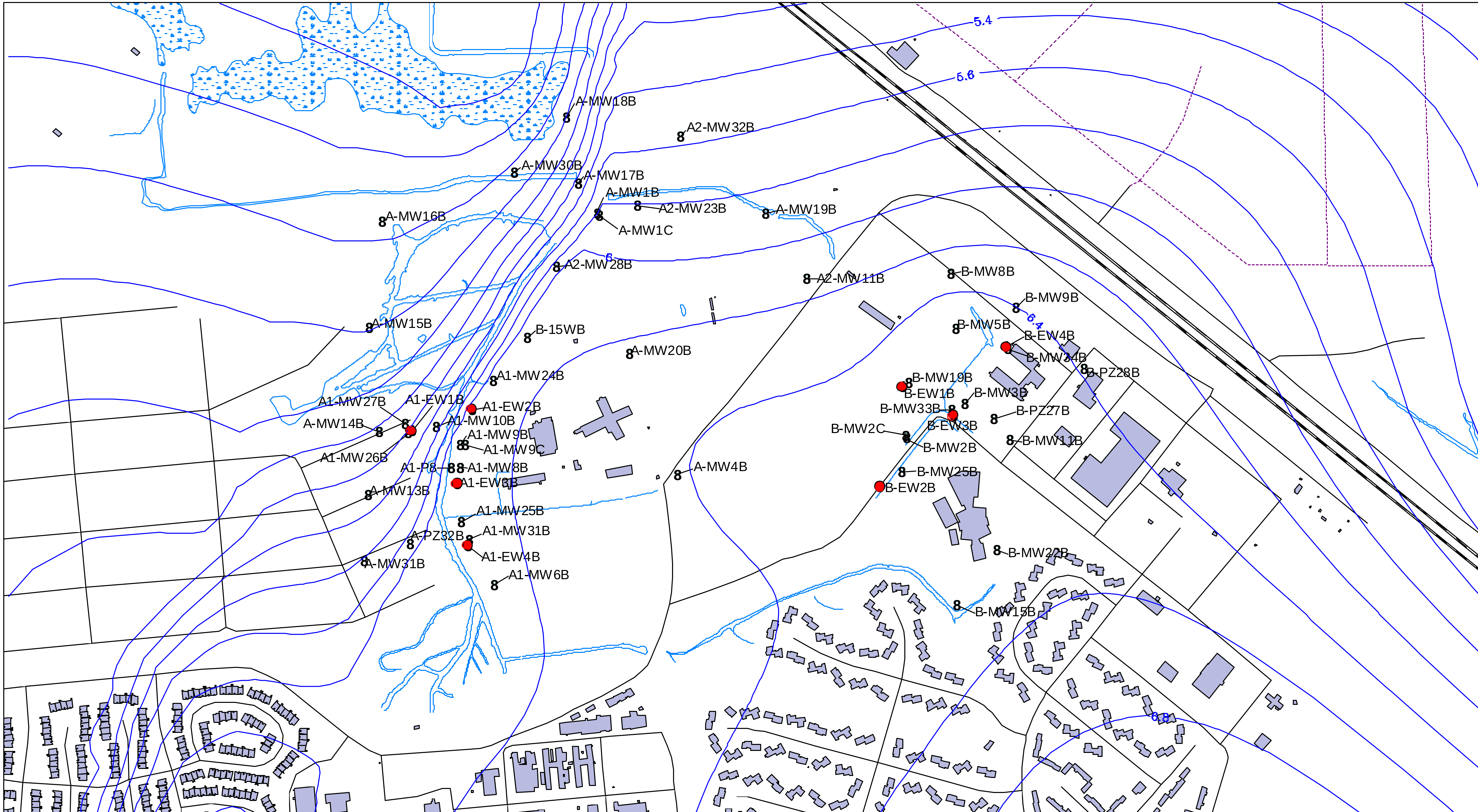
Simulated Non-pumping Calibration Hydraulic Heads – Layer 1

Camp Allen Landfill Groundwater Modeling

Naval Station Norfolk

CH2MHILL

File Path: c:\18gis\nsn\nsn-egisjt.apr



LEGEND

- 8 Monitoring Well, Piezometer, or Soil Boring
- Extraction Well
- Shoreline
- Runway
- Taxiway
- Arterial
- Alley
- Collector
- Interstate
- Local Road
- Ramp
- Buildings
- Simulated Groundwater Elevation

Contour Interval = 0.2 feet

N

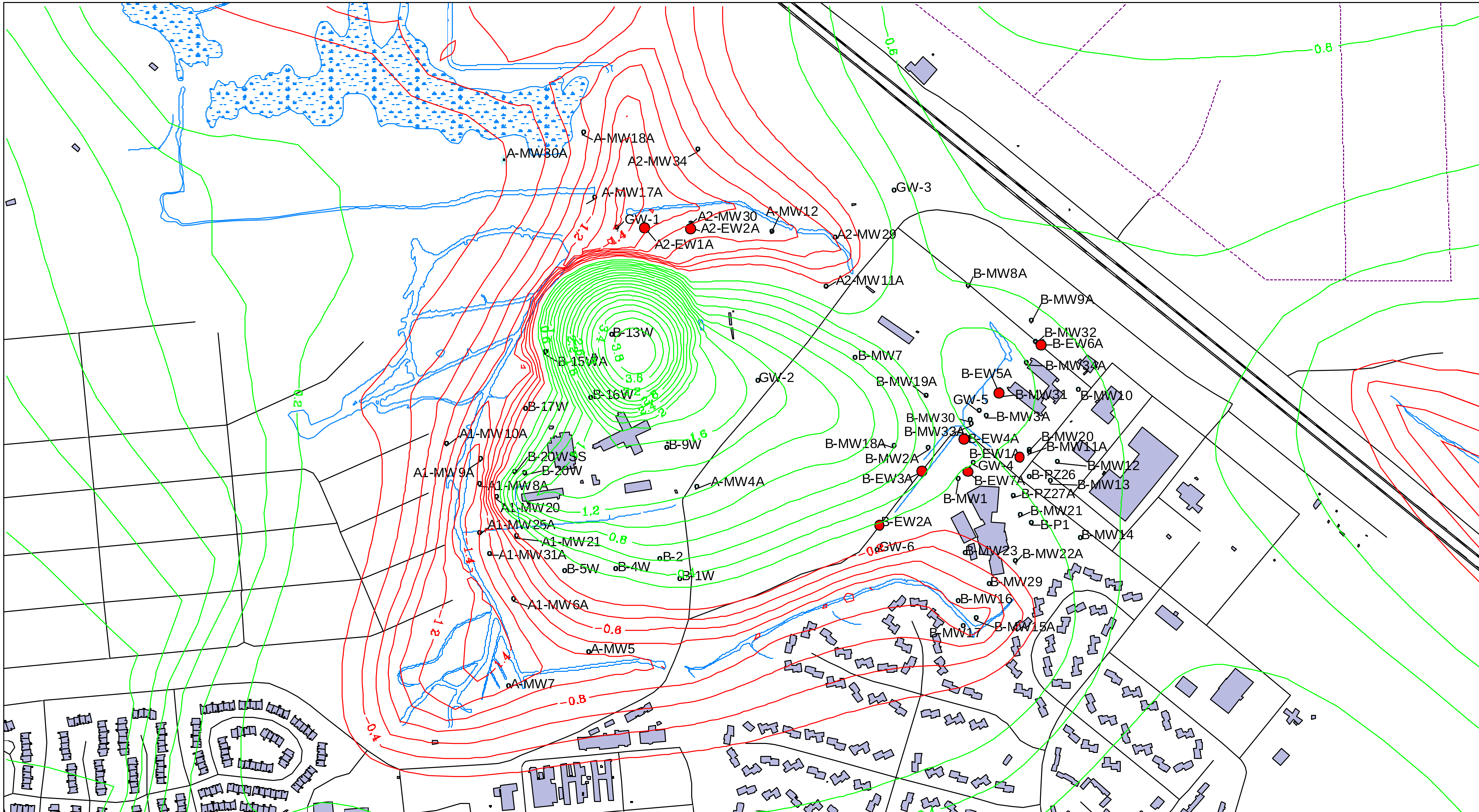
500 0 500 1000 Feet

Figure 5-11
Simulated Non-pumping Calibration Hydraulic Heads – Layer 2

Camp Allen Landfill Groundwater Modeling
Naval Station Norfolk

CH2MHILL

File Path: c:\18gis\nsn\nsn-egisjt.apr



LEGEND

- Monitoring Well, Piezometer, or Soil Boring
- Extraction Well
- Shoreline
- Runway
- Taxiway
- Arterial
- Alley
- Collector
- Interstate
- Local Road
- Ramp
- Buildings

N

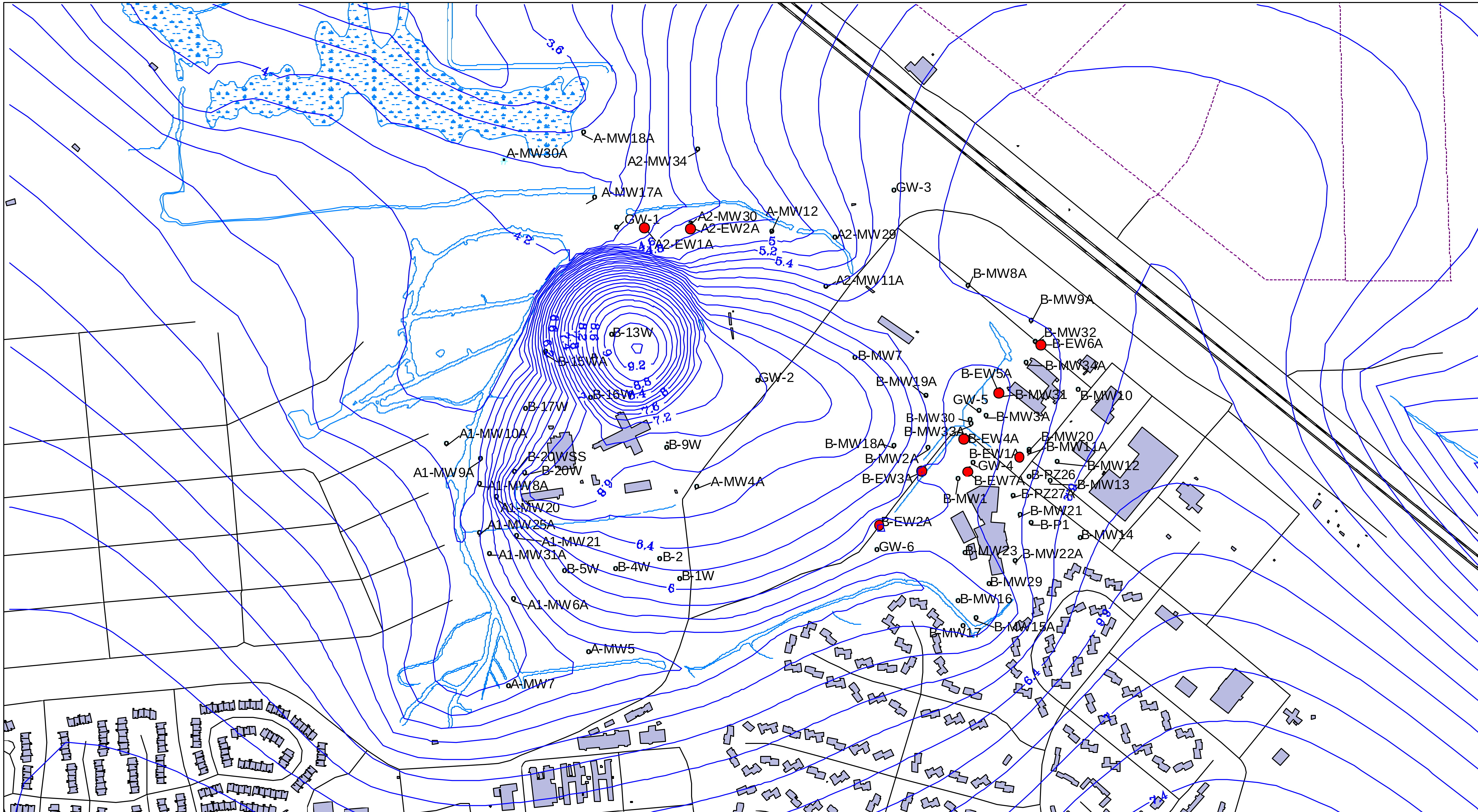
500 0 500 1000 Feet

Figure 5-12
Simulated Directions of Vertical Flow

Camp Allen Landfill Groundwater Modeling
Naval Station Norfolk

CH2MHILL

File Path: c:\18gis\nsn\nsn-egisjt.apr



LEGEND

- Monitoring Well, Piezometer, or Soil Boring
- Extraction Well
- Shoreline
- Runway
- Taxiway
- Arterial
- Alley
- Collector
- Interstate
- Local Road
- Ramp
- Buildings

N

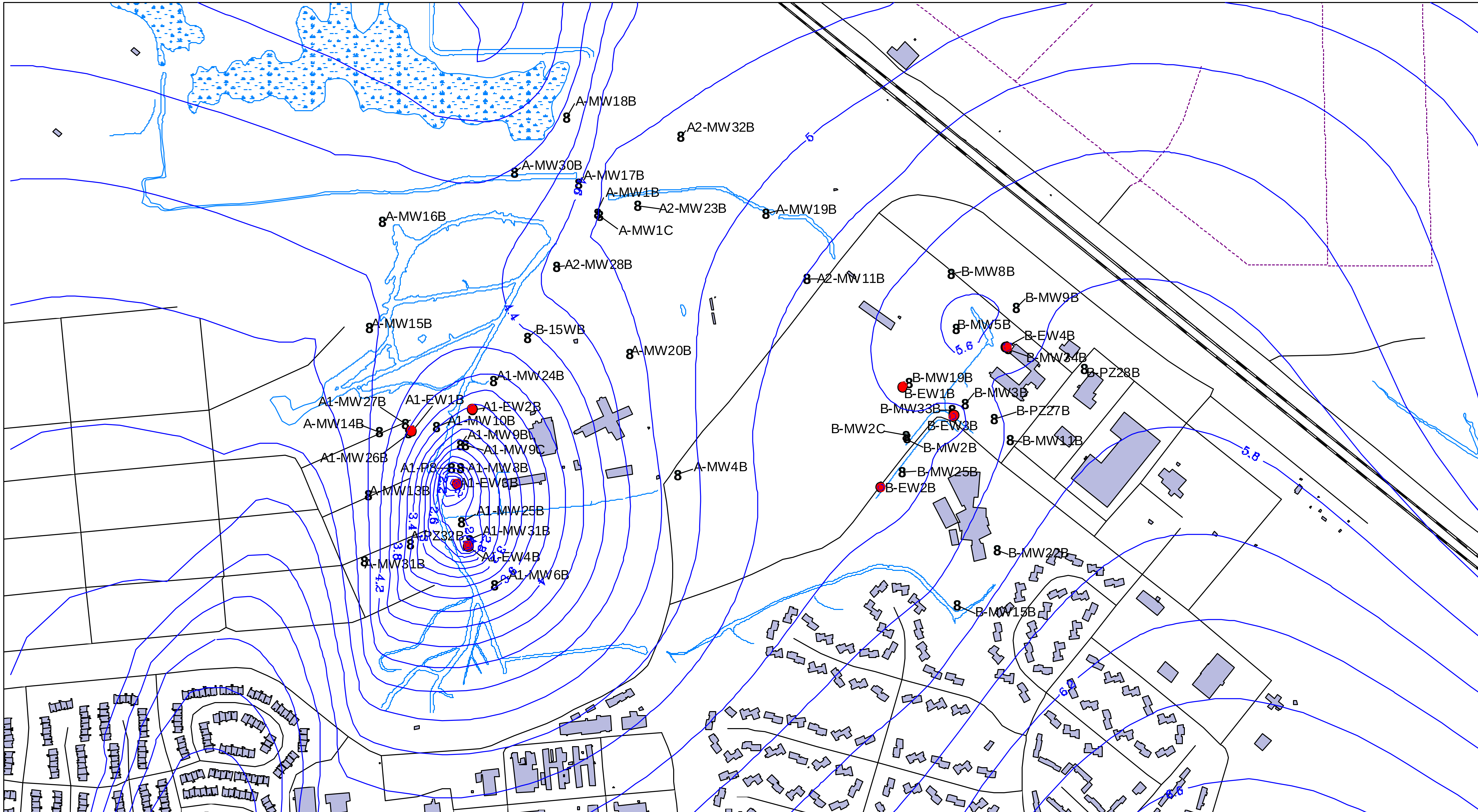
500 0 500 1000 Feet

Figure 5-13
Simulated Hydraulic Heads
with Extraction Wells Pumping (Verification) – Layer 1

Camp Allen Landfill Groundwater Modeling
Naval Station Norfolk

CH2MHILL

File Path: c:\18gis\nsn\nsn-egisjt.apr



LEGEND

- 8 Monitoring Well, Piezometer, or Soil Boring
- Extraction Well
- Shoreline
- Runway
- Taxiway
- Arterial
- Alley
- Collector
- Interstate
- Local Road
- Ramp
- Buildings

N

500 0 500 1000 Feet

Figure 5-14
Simulated Hydraulic Heads
with Extraction Wells Pumping (Verification) – Layer 2

Camp Allen Landfill Groundwater Modeling
Naval Station Norfolk

CH2MHILL

SECTION 6

Current Pumping Capture Zone Delineation

Particle tracking was performed using the USGS particle tracking program known as MODPATH (Pollock, 1994) to delineate capture zone extents under current pumping conditions. Regular arrays of starting particles were placed in Layers 1 and 2. Forward tracking of the particles was conducted under calibrated steady-state groundwater flow conditions with extraction wells pumping at March 2000 average monthly rates. Tracking continued until all particles exited the model at various discharge points, including extraction wells, drains, and rivers.

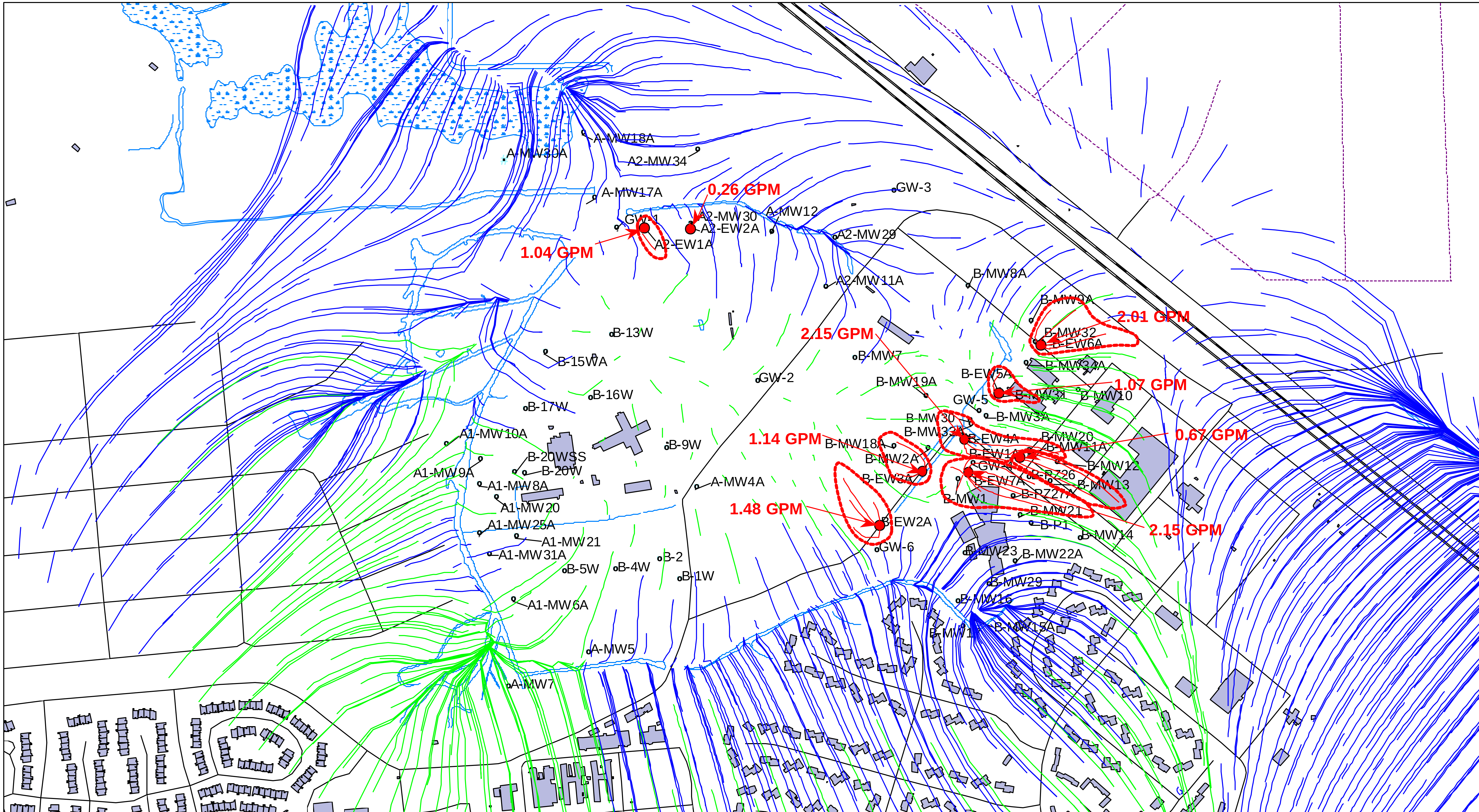
The results of the particle tracking simulation are represented by the particle pathlines shown in Figures 6-1 through 6-3. Red pathlines represent all particles exiting the model through extraction wells in Layer 1, despite which layer the particles were initialized. Green pathlines represent all particles that exit the model through extraction wells in Layer 2. Blue pathlines represent all particles that exit the model through other discharge boundaries in either layer.

6.1 Capture Zones of Layer 1 Extraction Wells – Columbia Aquifer

Figure 6-1 shows the capture zones (red dashed lines) of Layer 1 extraction wells (shallow Columbia aquifer). In Area A, the capture zones of extraction wells A2-EW1A and A2-EW2A have limited lateral extents due to the low pumping rates and relatively low hydraulic conductivity within the Columbia aquifer. Because no other extraction wells are operating in Area A due to unsustainable well yields, particles throughout much of Area A are either captured by Layer 2 extraction wells (green pathlines) or exit along other discharge points (blue pathlines), including drains representing Bousch Creek. In Area B, the capture zones of the various shallow extraction wells have greater lateral extents than those in Area A due to higher hydraulic conductivity and, in some cases, higher pumping rates. However, the capture zones in Area B are surrounded by green particle pathlines, indicating capture by Layer 2 extraction wells. This suggests that the capture zones in Layer 1 may be limited by pumping in Layer 2.

Figure 6-2 shows pathlines in both model layers for particles started only in Layer 1. Many of the particles started in Areas A and B travel a relatively short distance in Layer 1 under the downward vertical gradients augmented by pumping in Layer 2. Once these particles reach Layer 2, they travel significantly greater distances towards Layer 2 extraction wells. It is interesting to note that a number of the particles started in Layer 1 in Area B are captured by extraction wells in Area A in Layer 2.

File Path: c:\18gis\nsn\nsn-egisjt.apr



LEGEND

- Monitoring Well, Piezometer, or Soil Boring
- Extraction Well
- Shoreline
- Runway
- Taxiway
- Arterial
- Alley
- Collector
- Interstate
- Local Road
- Ramp
- Buildings

N

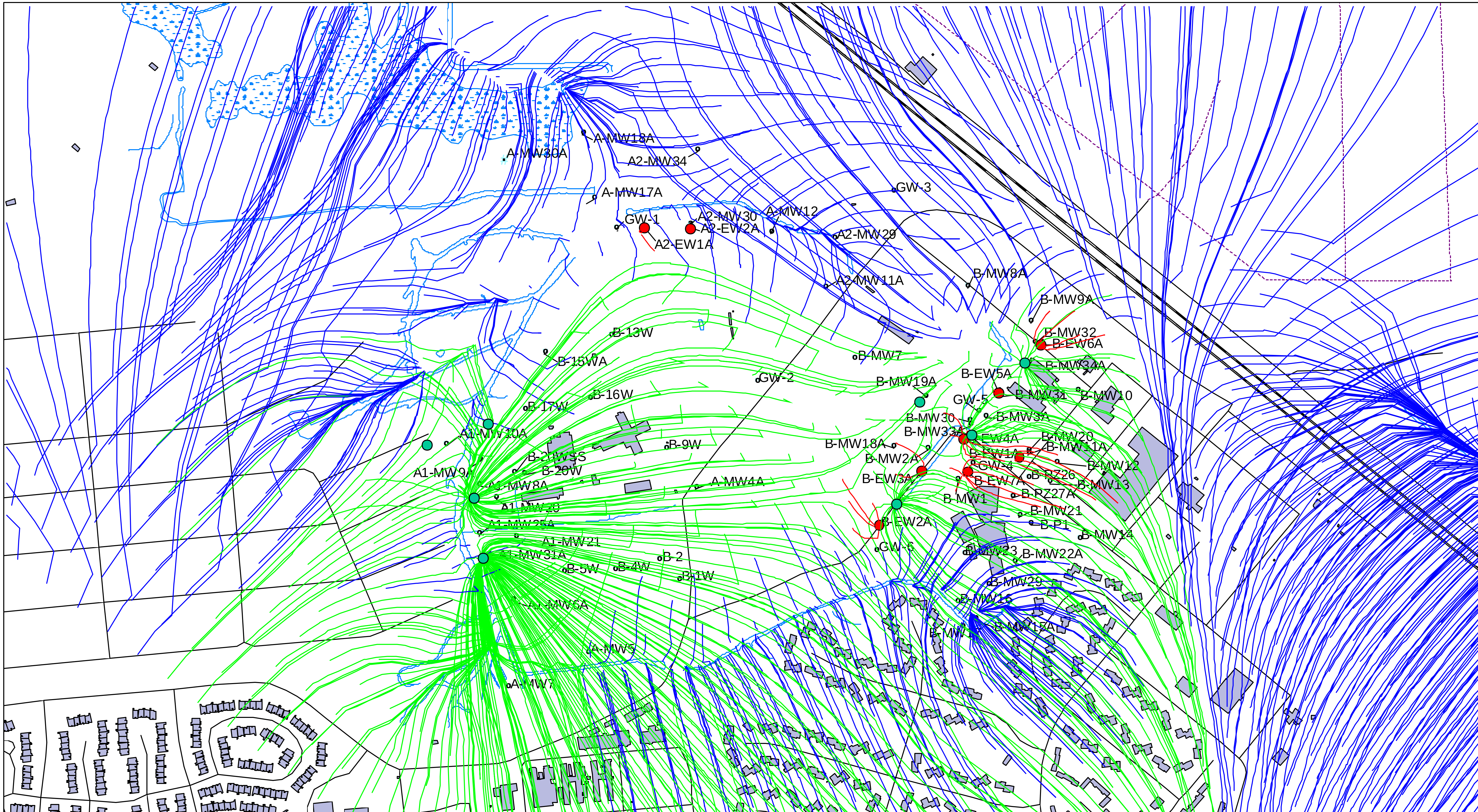
500 0 500 1000 Feet

Figure 6-1
Flow Lines and Capture Zones in Layer 1,
Layer 1 Extraction Wells Pumping 12 gpm

Camp Allen Landfill Groundwater Modeling
Naval Station Norfolk

CH2MHILL

File Path: c:\18gis\nsn\nsn-egisjt.apr



LEGEND

- Monitoring Well, Piezometer, or Soil Boring
- Extraction Well
- Shoreline
- Runway
- Taxiway
- Arterial
- Alley
- Collector
- Interstate
- Local Road
- Ramp
- Buildings

N

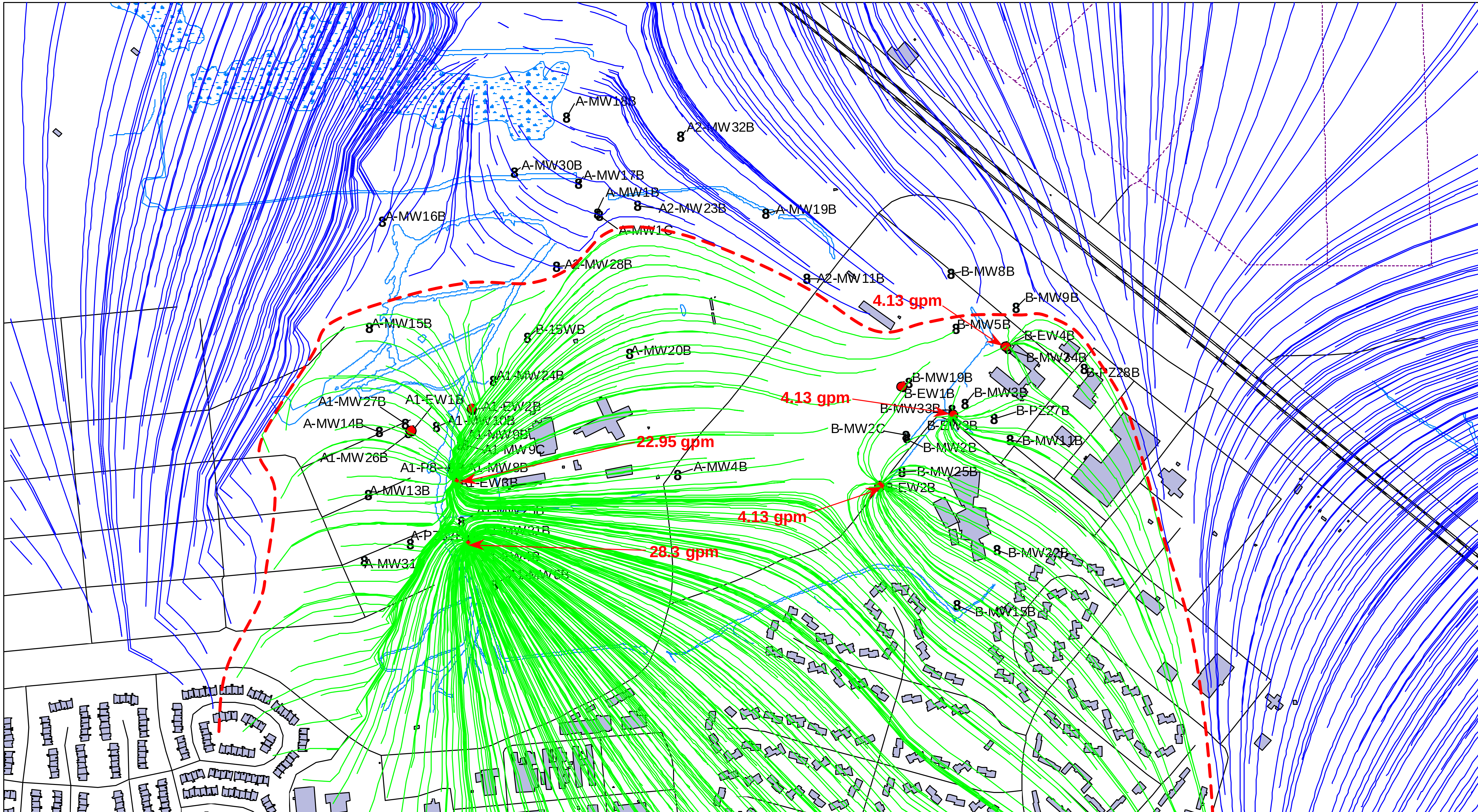
500 0 500 1000 Feet

Figure 6-2
Flow Lines in Both Layers of Particles Started in Layer 1

Camp Allen Landfill Groundwater Modeling
Naval Station Norfolk

CH2MHILL

File Path: c:\18gis\nsn\nsn-egisjt.apr



LEGEND

8 Monitoring Well, Piezometer, or Soil Boring
Extraction Well
Shoreline
Runway
Taxiway
Arterial
Alley
Collector
Interstate
Local Road
Ramp
Buildings

N

500 0 500 1000 Feet

Figure 6-3
Flow Lines and Capture Zones in Layer 2,
Layer 2 Extraction Wells Pumping 64 gpm

Camp Allen Landfill Groundwater Modeling
Naval Station Norfolk

CH2MHILL

6.2 Capture Zones of Layer 2 Extraction Wells – Yorktown-Eastover Aquifer

Figure 6-3 shows the capture zones in Layer 2 of the Layer 2 extraction wells (deeper Yorktown-Eastover aquifer), which have coalesced into a large capture zone (red dashed line). This large capture zone covers most of the site, but does not extend to the northwestern portion of the site near observation wells A-MW30B and A-MW17B where VOCs have been detected above the cleanup goals in the deep aquifer . Due to their higher pumping rates, extraction wells A1-EW3B and A1-EW4B capture particles, and thus groundwater, over a greater lateral extent than those in Area B. The higher pumping rates of the deeper wells also explain why a significant portion of the particles from Layer 1 are captured in Layer 2.

SECTION 7

Summary

A quasi-three-dimensional groundwater flow model of Camp Allen Landfill has been developed for the purpose of evaluating the effectiveness of the existing groundwater extraction system. These extraction wells are screened in either the unconsolidated sediments of the surficial Columbia aquifer or the underlying Yorktown–Eastover aquifer. The aquifers are separated by the Yorktown confining unit.

Camp Allen is located on a peninsula that is bordered on the north by Willoughby Bay, on the west by the Elizabeth River, and on the south by the Lafayette River. Conceptually, groundwater flow in the shallow Columbia aquifer is typically under unconfined conditions and is mainly driven by distributed recharge at the ground surface. Groundwater discharges to various local surface water features, including Bousch Creek, but also to the underlying Yorktown-Eastover aquifer under downward vertical gradients. Groundwater flow in the Yorktown-Eastover aquifer varies from confined or semi-confined to unconfined conditions, depending on the presence or absence of the Yorktown confining unit. It is driven mainly by major regional water bodies, but also by vertical leakage through its confining unit.

Analyses of aquifer pumping tests performed from March 28 through April 21, 2000, provided aquifer properties to be used in the model. A total of nine pumping tests were conducted, five in the shallow Columbia aquifer and four in the deeper Yorktown-Eastover aquifer. Horizontal hydraulic conductivity values for the Columbia aquifer ranged from 43.9 to 55.6 feet/day at Area B wells. Transmissivity values for the Yorktown-Eastover aquifer ranged from 2,005.6 to 3,017.8 $feet^2$/day at Area A wells and from 856.7 to 1,105.6 $feet^2$/day at Area B wells. Vertical hydraulic conductivities for both aquifers were estimated assuming horizontal to vertical hydraulic conductivity ratio of 10:1 based on the presence of clay beds interlayered with the silty sands of the Columbia or the shelly sands of the Yorktown-Eastover. Vertical hydraulic conductivity values for the Yorktown confining unit ranged from 0.015 to 0.11 feet/day at Area A wells and 6.4×10^{-20} to 0.0042 feet/day at Area B wells.

The model grid consists of two layers, 157 rows, and 158 columns with variable horizontal grid spacing ranging from approximately 20 to 300 feet. The grid is rotated such that the columns are oriented at a 38.5-degree angle to the direction of north. Due to the quasi-three-dimensional design of the model, model Layer 1 represents the shallow Columbia aquifer and model Layer 2 represents the deeper Yorktown-Eastover aquifer. The intervening Yorktown confining unit was not directly represented in the model by a model layer, but instead accounted for by the leakance term specifying the transmissive nature between model Layers 1 and 2. External boundary conditions in the model included prescribed heads and general head boundaries representing stage levels of major water bodies and regional inflow / outflow between the peninsula and land areas eastward. Internal boundary conditions included the Camp Allen extraction wells, as well as drains and rivers representing various local surface water bodies.

The primary computer code used in the modeling was the USGS's MODFLOW code. The groundwater flow model was calibrated to and verified with groundwater elevations measured at on-site monitoring wells and associated hydraulic gradients. Groundwater elevations measured during the July 1998 event served as calibration targets for the hydraulic head solution and those measured during the March 2000 event served as verification targets. Calibrating the model to July 1998 (non-pumping) groundwater flow conditions required various modifications to the initial model to match observed heads and gradients in both aquifers. Some further modifications were made based on the verification simulation. Altogether, these modifications included the addition of lower hydraulic conductivity zones in the Columbia aquifer, zones of either higher or lower leakance between the aquifers, and a lower transmissivity zone in the Yorktown-Eastover aquifer. Both the mean error and root mean square of the residuals were less than 1 foot in either model layer for both the calibration and verification simulations.

Particle tracking was performed using the USGS's MODPATH code to delineate capture zone extents under current pumping conditions. Forward tracking was conducted under calibrated steady-state groundwater flow conditions with extraction wells pumping at March 2000 average monthly rates. The results of the particle tracking simulation indicated that shallow Columbia aquifer extraction wells currently capture groundwater over limited extents due the low hydraulic conductivity of the aquifer material as well as the low pumping rates. In Area A, the capture zones of extraction wells A2-EW1A and A2-EW2A are virtually ineffective. In Area B, the capture zones have greater lateral extents than those in Area A, but these zones tend to be narrow and do not coalesce. The capture zones of the deeper Yorktown-Eastover aquifer extraction wells extend a large, coalesced area that covers most of the site. However, the capture zone does not extend to the northwestern portion where volatile and metals contamination has more recently been detected. Due to their higher pumping rates, the deeper wells also capture a significant portion of groundwater from shallow Columbia aquifer, especially where in proximity to “holes” in the Yorktown confining unit.

SECTION 8

References

Anderson, M.P. and W.W. Woessner. *Applied Groundwater Modeling, Simulation of Flow and Advective Transport*. Academic Press. San Diego, California. 1992. 381 p.

Fetter, C.W. *Applied Hydrogeology, Third Edition.* Prentice Hall. Englewood Cliffs, New Jersey. 1994. 691 p.

Freeze, R.A. and J.A. Cherry. *Groundwater*. Prentice-Hall. Englewood Cliffs, New Jersey. 1979. 604 p.

Hantush, M.S. and C.E. Jacob. Non-steady radial flow in an infinite leaky aquifer. *American Geophysical Union Transactions*. v. 36. 1955. pp. 95-100.

Harsh, J.F. and R.J. Laczniak. Conceptualization and Analysis of Ground-Water Flow System in the Coastal Plain of Virginia and Adjacent Parts of Maryland and North Carolina. U.S. Geological Survey Professional Paper 1404-F. 1990. 100 p.

HydroSOLVE, Inc. *AQTESOLV for Windows.* Version 2.15-Professional. 1996.

McDonald, M.G. and A.W. Harbaugh. *A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model.* Techniques of Water-Resources Investigations of the U.S. Geological Survey. Book 6, Chapter A1. 1988. 300+ p.

Meng III, A. A. and J. F. Harsh. *Hydrogeologic Framework of the Virginia Coastal Plain, Regional Aquifer-System Analysis.* U.S. Geological Survey Professional Paper 1404-C. 1988. 82 p.

Pollock, D.W. *User's Guide for MODPATH/MODPATH-PLOT, Version 3: A particle tracking post-processing package for MODFLOW, the U.S. Geological Survey finite-difference ground-water flow model.* U.S. Geological Survey Open-File Report 94-464, 1994. 6 ch.

Theis, C.V. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage. *Transactions of the American Geophysical Union,* 16. 1935. pp. 519-524.

Appendix A
Aquifer Pumping Test Description, Analyses, and Results

A.1 Introduction

Initial aquifer properties of hydraulic conductivity, transmissivity, and leakance assigned to the model were based on aquifer pumping tests performed from March 28 through April 21, 2000. A total of nine pumping tests were conducted, five in the shallow Columbia aquifer and four in the deeper Yorktown-Eastover aquifer. The tests were conducted for a duration of 72 hours for the deep wells and 24 hours for the shallow wells.

A.2 Aquifer Pumping Test Methodology

The extraction wells tested, as well as those that potentially could have impacted the test wells, were shut down at least 24 hours in advance of the tests. The pumping tests were conducted concurrently two at a time.

Immediately prior to the tests, static groundwater elevation measurements were collected manually from the test wells and nearby monitoring wells. During the pumping tests, groundwater levels were measured using pressure transducer data logger systems. Pressure transducers were installed in the test wells and the monitoring wells selected as observation wells for the tests. The data logger systems were programmed to record water levels on a logarithmic cycle. During the first and last four hours of the tests, a field geologist collected groundwater level measurements manually to confirm the data logger measurements.

At the end of the tests, the extraction wells were shut down and remained so while the data logger systems continued to measure water levels until either the levels recovered 90 percent of their maximum drawdown or four hours had passed, whichever came first. Subsequently, the water level data from the data loggers was downloaded to a computer for analysis.

A.2.1 Yorktown-Eastover Aquifer Pumping Tests (Deep)

The aquifer pumping tests using extraction wells A1-EW4B in Area A and B-EW3B in Area B were conducted simultaneously from March 28 through March 31, 2000. The aquifer pumping tests using extraction wells A1-EW3B in Area A and B-EW4B were conducted simultaneously from April 3 through April 6, 2000. Prior to all these aquifer pumping tests, the entire extraction system was shut down on March 24, 2000, to allow water levels to recover to static levels.

A.2.1.1 A1-EW4B Constant Rate Aquifer Test

The constant rate aquifer pumping test with extraction well A1-EW4B as the pumping well was conducted from March 28 through March 31, 2000. Observation wells selected for the A1-EW4B test included monitoring wells A1-MW25B and A1-MW31B. Water level observations were also recorded in monitoring wells A1-MW25A and A1-MW31A to assess the degree of hydraulic connection between the Columbia and Yorktown-Eastover aquifers in the vicinity of A1-EW4B. Pumping started in A1-EW4B at a rate of 38 gallons per minute (gpm) at 13:52 on March 28, 2000. The pumping rate varied from 36.5 to 39 gpm during the test. At approximately 42.5 hours into the test, rain began to fall and continued for at least 6 hours. The pump in A1-EW4B was stopped after approximately 71 hours of pumping. Total pumpage as measured by the flow meter at A1-EW4B was approximately 156,054 gallons. All data loggers were shut off 3.4 to 4 hours after pumping had stopped (after 80 to 90 percent recovery of initial water levels).

A.2.1.2 B-EW3B Constant Rate Aquifer Test

The constant rate aquifer pumping test with extraction well B-EW3B as the pumping well was conducted from March 28 through March 31, 2000. Monitoring well B-MW33B was selected as the observation well for this test. Water level observations were also recorded in monitoring well B-MW33A to assess the degree of hydraulic connection between the Columbia and Yorktown-Eastover aquifers in the vicinity of B-EW3B. Pumping started in B-EW3B at a rate of 6 gpm at 15:00 on March 28, 2000. The pumping rate remained consistent at a rate of 6 gpm during the test. Approximately 18.5 hours into the test, a lawnmower severed the pressure transducer cable in B-EW3B and it had to be replaced. Due to the malfunctioning of the first replacement, a second replacement data logger had to be placed in B-EW3B before the measurement of water levels could be resumed. At approximately 41.5 hours into the test, rain began to fall and continued for at least 6 hours. The pump in B-EW3B was stopped after approximately 72 hours of pumping. Total pumpage as measured by the flow meter at B-EW3B was approximately 25,271 gallons. All data loggers were shut off 2.4 hours after pumping had stopped (after 80 to 90 percent recovery of initial water levels).

A.2.1.3 A1-EW3B Constant Rate Aquifer Test

The constant rate aquifer pumping test with extraction well A1-EW3B as the pumping well was conducted from April 3 through April 6, 2000. Observation wells selected for the A1-EW3B test included monitoring wells A1-MW8B and A1-P8. Water level observations were also recorded in monitoring wells A1-MW8A and A1-MW20 to assess the degree of hydraulic connection between the Columbia and Yorktown-Eastover aquifers in the vicinity of A1-EW3B. Pumping started in A1-EW3B at a rate of 37 gpm at 12:33 on April 3, 2000. The pumping rate varied from 33 to 37 gpm during the test. At approximately 22.7 hours into the test, rain began to fall. It was noted during the test that the water level in A1-MW20, as measured by the pressure transducer, did not correspond to the manual water level measurements. The pump in A1-EW3B was stopped after approximately 72.6 hours of pumping. Total pumpage as measured by the flow meter at A1-EW3B was approximately 159,447 gallons. All data loggers were shut off 2.1 hours after pumping had stopped (after 80 to 90 percent recovery of initial water levels).

A.2.1.4 B-EW4B Constant Rate Aquifer Test

The constant rate aquifer pumping test with extraction well B-EW4B as the pumping well was conducted from April 3 through April 6, 2000. Monitoring well B-MW34B was selected as the observation well for this test. Water level observations were also recorded in monitoring well B-MW34A to assess the degree of hydraulic connection between the Columbia and Yorktown-Eastover aquifers in the vicinity of B-EW4B. Pumping started in B-EW4B at an initial rate of 7 gallons per minute at 11:02 on April 3rd, 2000. This rate was reduced to 5.5 gpm shortly after pumping began. The pumping rate in B-EW4B appeared to remain consistent at 5.5 gpm during the test. At approximately 24 hours into the test, rain began to fall. The pump in B-EW4B was stopped after approximately 71 hours of pumping. Total pumpage as measured by the flow meter at B-EW4B was approximately 23,684 gallons. All data loggers were shut off 2 hours after pumping had stopped (after 80 to 90 percent recovery of initial water levels).

A.2.2 Columbia Aquifer Pumping Tests (Shallow)

The aquifer pumping tests using extraction wells A2-EW2A in Area A and B-EW1A in Area B were conducted simultaneously from April 10 through April 11, 2000. The aquifer pumping tests using extraction wells B-EW4A and B-EW6A in Area A were conducted simultaneously from April 12 through April 13, 2000. During these tests, the deeper Yorktown-Eastover extraction wells in Area A were operating. The aquifer pumping test using extraction well B-EW5A was conducted from April 20 through April 21, 2000. Prior to the B-EW5A test, the pumps for the entire extraction system were turned on.

A.2.2.1 A2-EW2A Aquifer Test

Two attempts to conduct the constant rate aquifer pumping test using extraction well A2-EW2A as the pumping well were made, one on April 10 and one on April 11, 2000. Monitoring well A2-MW30 was selected as the observation well for this test. On the first attempt, pumping at a rate of 0.8 gpm in A2-EW2A lowered the water level below the position of the pressure transducer in approximately 43 minutes. Prior to the second attempt, the pressure transducer was set lower in A2-EW2A. During the second attempt, the pump in A2-EW2A stopped running (burned out) after having pumped the well dry in 2.3 hours at a rate of 0.5 gpm. In both attempts, recovery was recorded by the data logger.

A.2.2.2 B-EW1A Aquifer Test

Three attempts to conduct the constant rate aquifer pumping test using extraction well B-EW1A as the pumping well were made, two on April 10 and one on April 11, 2000. Monitoring wells B-MW11A, B-P1, and B-MW20 were selected as the observation wells for this test. On the first attempt, the pump in A2-EW2A shut off 5 minutes after the test began. Also, the pressure transducer in B-MW20 malfunctioned and had to be replaced. Approximately 25 minutes after the pump shut off, the test was restarted (second attempt) at a pumping rate of 1.5 gpm. However, manual measurement of the water level in B-EW1A indicated that the well had not fully recovered prior to restarting the test and pumping was stopped 36 minutes into the test. Prior to the third attempt on April 11, the pressure transducer in B-MW20 again malfunctioned and had to be replaced. On the third attempt, the pump in B-EW1A stopped during the first 2 hours of the test after having pumped the well dry at a rate of 1.5 gpm. The pump subsequently restarted after the water level in the well had recovered approximately two feet. Due to the inability to sustain pumping in B-EW1A, the test was stopped and the final recovery was recorded by the data logger.

A.2.2.3 B-EW4A Aquifer Test

The aquifer pumping test with extraction well B-EW4A as the pumping well was conducted from April 12 through April 13, 2000. Monitoring well B-MW30 was selected as the observation well for this test. Pumping started in B-EW4A at an initial rate of 2 gpm at 10:18 on April 12, 2000. This rate was increased to 4 gpm after approximately 4 hours of pumping, then to 6 gpm after approximately 4.7 hours of pumping. The pump in B-EW4A was stopped after approximately 24 hours of pumping. Total pumpage as measured by the flow meter at B-EW4A was approximately 7,502 gallons. The data logger was shut off 4 hours after pumping had stopped (after 80 to 90 percent recovery of initial water levels).

A.2.2.4 B-EW6A Aquifer Test

The aquifer pumping test with extraction well B-EW6A as the pumping well was conducted from April 12 through April 13, 2000. Monitoring well B-MW32 was selected as the observation well for this test. Pumping started in B-EW6A at an initial rate of 2 gpm at 10:09 on April 12, 2000. This rate was increased to 4 gpm after approximately 4 hours of pumping, then to 5 gpm after approximately 5 hours of pumping. The pump in B-EW6A was stopped after approximately 24 hours of pumping. Total pumpage as measured by the flow meter at B-EW6A was approximately 6,403 gallons. The data logger was shut off 3.8 hours after pumping had stopped (after 80 to 90 percent recovery of initial water levels).

A.2.2.5 B-EW5A Aquifer Test

The aquifer pumping test with extraction well B-EW5A as the pumping well was conducted from April 20 through April 21, 2000. Monitoring well B-MW31 was selected as the observation well for this test. Pumping started in B-EW5A at an initial rate of 3.7 gpm at 10:08 on April 20, 2000. This rate was increased to 5 gpm after approximately 4.3 hours of pumping. The pump in B-EW5A was stopped after approximately 24 hours of pumping. Total pumpage as measured by the flow meter at B-EW5A was approximately 56,300 gallons. The data logger was shut off less than 30 minutes after pumping had stopped (after 80 to 90 percent recovery of initial water levels).

A.3 Aquifer Pumping Test Analysis

The aquifer test data were analyzed using the AQTESOLV (HydroSOLVE, Inc., 1996) software package to obtain estimates of transmissivity / hydraulic conductivity and storativity. For the Yorktown-Eastover aquifer pumping test data, the Hantush-Jacob solution (Hantush and Jacob, 1955) for leaky artesian aquifers provided the best fit to the drawdown data. For the Columbia aquifer pumping test data, the confined Theis (1935) solution provided the best fit to the drawdown data because only the compressive storage response was observed. Both solutions were fitted to the data on log-log plots of displacement versus time. For the Yorktown-Eastover aquifer tests, aquifer thicknesses used in the analyses varied from approximately 78.2 to 94.6 feet and were estimated from the known elevation of the top of the Yorktown-Eastover aquifer at each observation well location and the lowest assumed elevation of –120 feet msl for the bottom of the Yorktown-Eastover aquifer based on the boring logs for deep wells. The saturated aquifer thicknesses used in analyzing the Columbia aquifer tests varied from 23.5 to 24.3 feet and were estimated from the pre-test static water level and the elevation of the bottom of the Columbia aquifer at each observation well location. Partial penetration effects were taken into account in the data analyses. No horizontal-to-vertical anisotropy factor was assumed.

A.4 Aquifer Pumping Test Results

The plots of displacement versus time for all observation wells except those for the A2-EW2A, B-EW1A, and B-EW5A aquifer pumping tests are shown in Appendix B. The drawdown data for the observation wells for these tests could not be analyzed for the following reasons: (1) both A2-EW2A and B-EW1A were pumped dry early in their respective tests; and (2) no drawdown was observed in the observation well for the B-EW5A test. For the analysis of the B-EW6A test, water level observations taken manually in observation well B-MW32 had to be analyzed due to the poor quality of the data recorded by the data logger.

A.4.1 Yorktown-Eastover Aquifer Pumping Test Results (Deep)

Measurements of maximum drawdown at the test wells and associated observation wells are provided in Table A-1. In Area A, maximum drawdown at A1-EW3B was nearly three times greater than that in test well A1-EW4B, despite virtually the same pumping rates and durations. If not due to well losses, this difference in maximum drawdown reflected the heterogeneous aspects of the aquifer material within Area A alone. The maximum drawdowns among Area B wells were more similar. Water levels noted during the tests in nearby shallow aquifer wells indicated drawdown in the Columbia aquifer as a result of pumping in the Yorktown-Eastover aquifer. Maximum drawdowns in the Columbia aquifer ranged from 0.1 to 0.5 feet. This likely reflected both leakage from the

Yorktown confining unit as well as direct leakage from the Columbia aquifer in proximity to “holes” in the confining unit.

TABLE A-1
Yorktown-Eastover Aquifer Pumping Test Results
Camp Allen Landfill Groundwater Modeling, Naval Station Norfolk, Norfolk, Virginia

Well ID	Radius from Pumping Well (feet)	Maximum Drawdown (feet)	Leaky Hantush-Jacob Solution T ($feet^2$/day)	S	r/B	K[a] (feet/day)	K[b] (feet/day)	c	K' (feet/day)
A1-EW3B Test									
A1-EW3B	0	17.5	--	--	--	--	--	--	--
A1-MW8B	87.1	1.5	2,005.6	1.84E-04	1.06E-01	23.3	9.7	3.34E+02	0.048
A1-P8	86.4	1.5	2,010.2	1.67E-04	1.11E-01	23.3	9.8	3.03E+02	0.049
A1-EW4B Test									
A1-EW4B	0	6	--	--	--	--	--	--	--
A1-MW25B	130	1.13	3,017.8	2.27E-04	5.51E-02	38.6	14.6	1.84E+03	0.015
A1-MW31B	28.8	2.2	2,283.1	6.37E-04	3.88E-02	29.2	11.1	2.41E+02	0.11
Area A Average			**2,329.2**	**3.04E-04**	**--**	**28.6**	**11.3**	**--**	**0.05**
B-EW3B Test									
B-EW3B	0	5.94	--	--	--	--	--	--	--
B-MW33B	32.1	0.72	1,105.6	1.75E-03	1.00E-10	12.2	5.4	9.33E+19	6.43E-20
B-EW4B Test									
B-EW4B	0	4.7	--	--	--	--	--	--	--
B-MW34B	10	1.3	856.7	1.64E-03	1.13E-02	9.1	4.2	9.15E+02	0.0042
Area B Average			**981.2**	**1.70E-03**	**--**	**10.6**	**4.8**	**--**	**0.0021**
Minimum			856.7	1.67E-04	--	9.1	4.2	--	6.43E-20
Maximum			3,017.8	1.75E-03	--	38.6	14.6	--	0.11
Average			1,879.8	7.68E-04	--	22.6	9.1	--	0.037

[a] Hydraulic conductivity estimated using minimum aquifer thickness based on boring logs, dependent upon location.
[b] Hydraulic conductivity estimated using 206-foot aquifer thickness estimated from Meng and Harsh (1988).
T: Transmissivity
S: Storativity
r: Radius from pumping well
B: Aquifer thickness
K: Aquifer hydraulic conductivity
C: Hydraulic resistance of semi-confining unit
K': Semi-confining unit hydraulic conductivity

Table A-1 summarizes the estimates of transmissivity, aquifer horizontal hydraulic conductivity, storativity, and confining unit vertical hydraulic conductivity from the analyses of the Yorktown-Eastover aquifer pumping test data. Transmissivity values at Area A wells ranged from 2,005.6 to 3,017.8 $feet^2/day$ and averaged 2,329.2 $feet^2/day$. At Area B wells, lower transmissivity values resulted, ranging from 856.7 to 1,105.6 $feet^2/day$ and averaging 981.2 $feet^2/day$. In general, the transmissivity values associated with Area A tended to be 2 to 3.5 times greater than those for Area B.

Given in Table A-1, hydraulic conductivity values were estimated using both the minimum aquifer thicknesses based on boring logs as well as the 206-foot aquifer thickness estimated from the top-of-aquifer elevation and confining unit thickness maps by Meng and Harsh (1988). Although typically of the same magnitude, the hydraulic conductivity values calculated from the minimum aquifer thicknesses were approximately twice those calculated using the 206-foot aquifer thickness. However, it is important to remember that the extraction wells screen only 20 feet in the upper portion of the Yorktown-Eastover aquifer. Due to the interbedding of shelly sand beds with thin clay layers within the aquifer, it is likely that the drawdown response observed in the extraction wells reflects only the upper portions of the total aquifer thickness. Therefore, the horizontal hydraulic conductivity values may in fact be higher than those reported in Table A-1.

Storativity values ranged from 1.67×10^{-4} to 6.37×10^{-4} with an average of 3.04×10^{-4} at Area A wells. Storativity values were higher at Area B wells, ranging from 1.64×10^{-3} to 1.75×10^{-3} with an average of 1.7×10^{-3}.

Estimated vertical hydraulic conductivity values for the Yorktown confining unit ranged from 0.015 to 0.11 feet/day and averaged 0.05 feet/day at Area A wells. At Area B wells, the vertical hydraulic conductivity values were lower, ranging from practically zero to 0.0042 feet/day and averaging 0.0021 feet/day.

A.4.2 Columbia Aquifer Pumping Test Results (Shallow)

Measurements of maximum drawdown at the test wells and associated observation wells are provided in Table A-2. Similar magnitudes of maximum drawdown were observed at observation wells B-MW30 and B-MW32 despite B-MW32 being approximately 60 feet closer to the test well than B-MW30. At B-MW31, which is located approximately 19 feet from test well B-EW5A, no measurable drawdown was observed. These observations reflect the heterogeneous character of the aquifer within Area B alone. However, comparisons between areas was not possible due to the only Area A test well, A2-EW2A, pumping dry after only 1.25 hours of pumping.

TABLE A-2
Columbia Aquifer Pumping Test Results
Camp Allen Landfill Groundwater Modeling, Naval Station Norfolk, Norfolk, Virginia

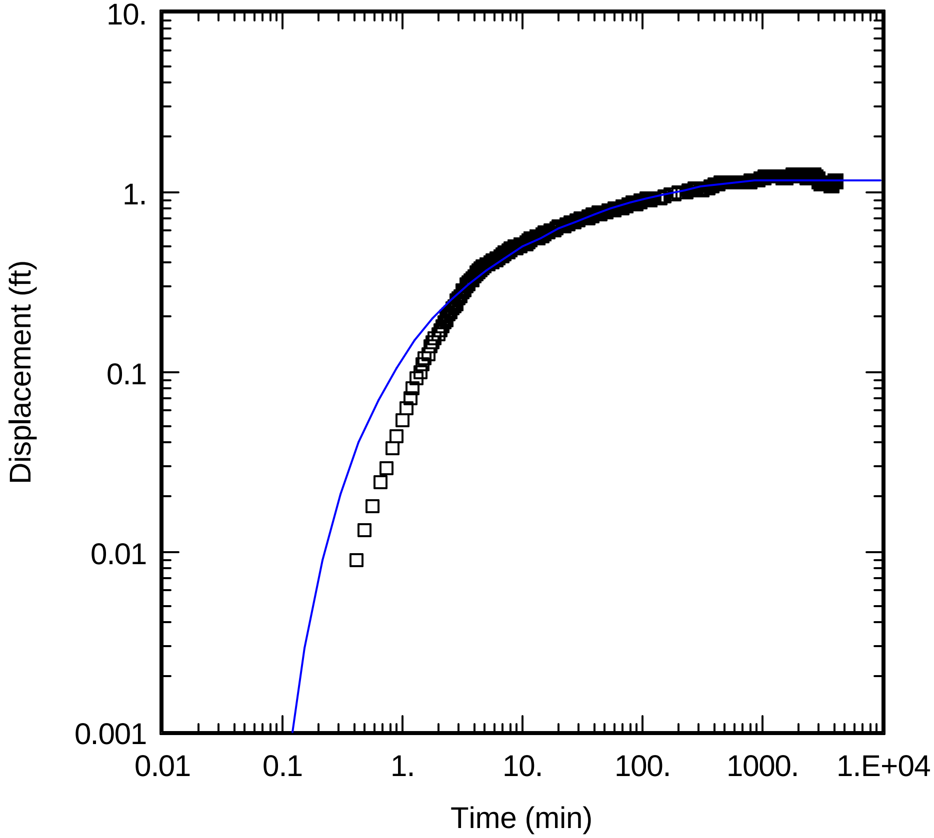
Well ID	Radius from Pumping Well (feet)	Maximum Drawdown (feet)	Confined Theis Solution		
			T (feet2/day)	S	K (feet/day)
A2-EW2A Test					
A2-EW2A	0	9		--well pumped dry--	
A2-MW30	12.4	0.04	--	--	--
B-EW1A Test					
B-EW1A	0	12.1		--well pumped dry--	
B-MW11A	51.9	0.05	--	--	--
B-P1	350.7	0.08	--	--	--
B-MW20	53.5	0	--	--	--
B-EW4A Test					
B-EW4A	0	7.5	--	--	--
B-MW30	93.5	0.3	1,307.1	4.56E-03	55.6
B-EW5A Test					
B-EW5A	0	11.4	--	--	--
B-MW31	19.3	0		--no observable drawdown--	
B-EW6A Test					
B-EW6A	0	7.5	--	--	--
B-MW32	34.8	0.2	1,058.0	6.35E-02	43.9
Area B Average			**1,182.6**	**3.40E-02**	**49.8**
Minimum			1,058.0	4.56E-03	43.9
Maximum			1,307.1	6.35E-02	55.6
Average			1,182.6	3.40E-02	49.8

T: Transmissivity
S: Storativity
K: Aquifer hydraulic conductivity

Table A-2 summarizes the estimates of transmissivity, horizontal hydraulic conductivity, and storativity from the analyses of the Columbia aquifer pumping test data. Horizontal hydraulic conductivity values for the Columbia aquifer ranged from 43.9 to 55.6 feet/day and averaged 49.8 feet/day for Area B wells. These hydraulic conductivity values were estimated from the corresponding transmissivity values provided by the Theis (1935) solution using the approximate saturated aquifer thickness at each location. The fact that pumping in one of the test wells in Area B resulted in no observable drawdown in an observation well less than 20 feet away, and that two test wells were pumped dry early in the test, one in Area B and one in Area A, indicates that portions of the Columbia aquifer on-site are associated with hydraulic conductivity values significantly lower than those estimated from the pumping test analyses. Because the test well pumped dry early in the test, no results were available for the Area A.

Storativity values, representing the initial release of groundwater from compressive storage, ranged from 4.56×10^{-3} to 6.35×10^{-2} and averaged 3.40×10^{-2} at Area B wells. No specific yield values were available from the pumping test analyses due to lack of observed gravity-yield response during the 24-hour pumping tests.

Appendix B
Log-log Plots of Displacement versus Time with Fitted Analytical Solutions



OBSERVATION WELL A1-MW25B

Data Set: C:\DOCUME~2\PROJECT\157392~1\APTDATA\A1-MW25B.A(
Date: 06/21/02 Time: 11:29:19

PROJECT INFORMATION

Company: CH2M Hill
Client: US Navy
Project: 157392.LT.01
Test Location: Camp Allen Landfill
Test Well: A1-EW4B
Test Date: March 28-31, 2000

SOLUTION

Aquifer Model: Leaky
Solution Method: Hantush-Jacob

T = 3017.8 ft^2/day
S = 0.0002271
r/B = 0.0551

AQUIFER DATA

Saturated Thickness: 78.16 ft

Anisotropy Ratio (Kz/Kr): 1.

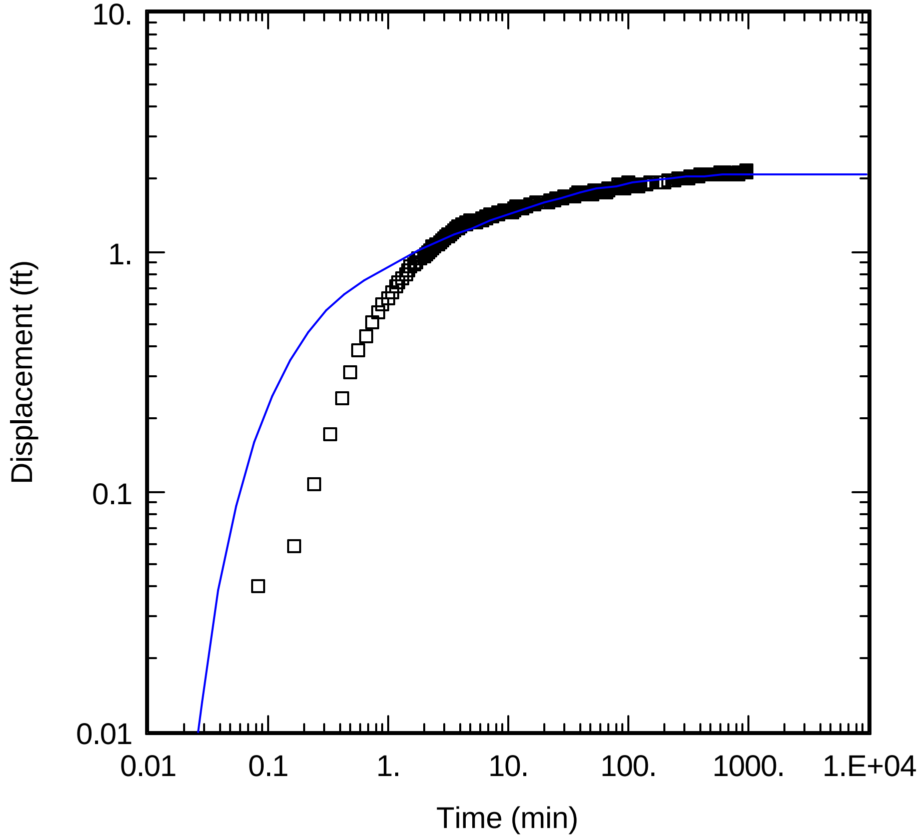
WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
A1-EW4B	1.212E+007	3.505E+006

Observation Wells

Well Name	X (ft)	Y (ft)
□ A1-MW25B	1.212E+007	3.505E+006



OBSERVATION WELL A1-MW31B

Data Set: C:\DOCUME~2\PROJECT\157392~1\APTDATA\A1-MW31B.A(
Date: 06/21/02 Time: 11:28:49

PROJECT INFORMATION

Company: CH2M Hill
Client: US Navy
Project: 157392.LT.01
Test Location: Camp Allen Landfill
Test Well: A1-EW4B
Test Date: March 28-31, 2000

SOLUTION

Aquifer Model: Leaky
Solution Method: Hantush-Jacob

T = 2283.1 ft^2/day
S = 0.0006369
r/B = 0.03877

AQUIFER DATA

Saturated Thickness: 78.16 ft

Anisotropy Ratio (Kz/Kr): 1.

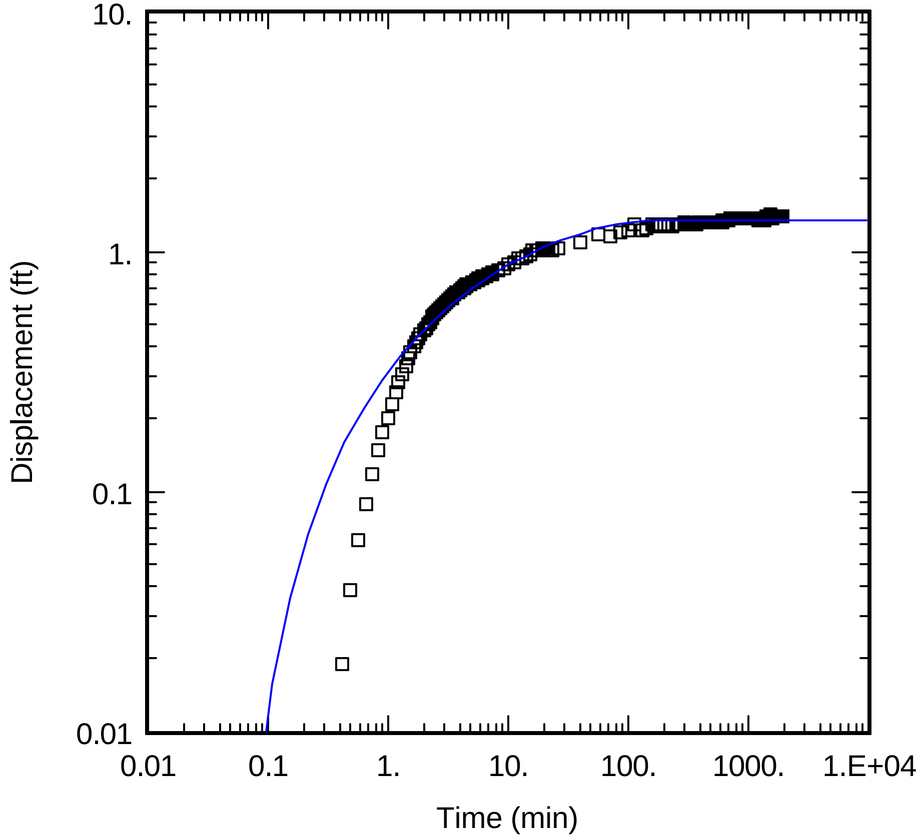
WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
A1-EW4B	1.212E+007	3.505E+006

Observation Wells

Well Name	X (ft)	Y (ft)
□ A1-MW31B	1.212E+007	3.505E+006



OBSERVATION WELL A1-MW8B

Data Set: C:\DOCUME~2\PROJECT\157392~1\APTDATA\A1-MW8B.AQ
Date: 06/21/02 Time: 11:29:09

PROJECT INFORMATION

Company: CH2M Hill
Client: US Navy
Project: 157392.LT.01
Test Location: Camp Allen Landfill
Test Well: A1-EW3B
Test Date: April 3-6, 2000

SOLUTION

Aquifer Model: Leaky
Solution Method: Hantush-Jacob

T = 2005.6 ft^2/day
S = 0.0001841
r/B = 0.1064

AQUIFER DATA

Saturated Thickness: 86.14 ft

Anisotropy Ratio (Kz/Kr): 1.

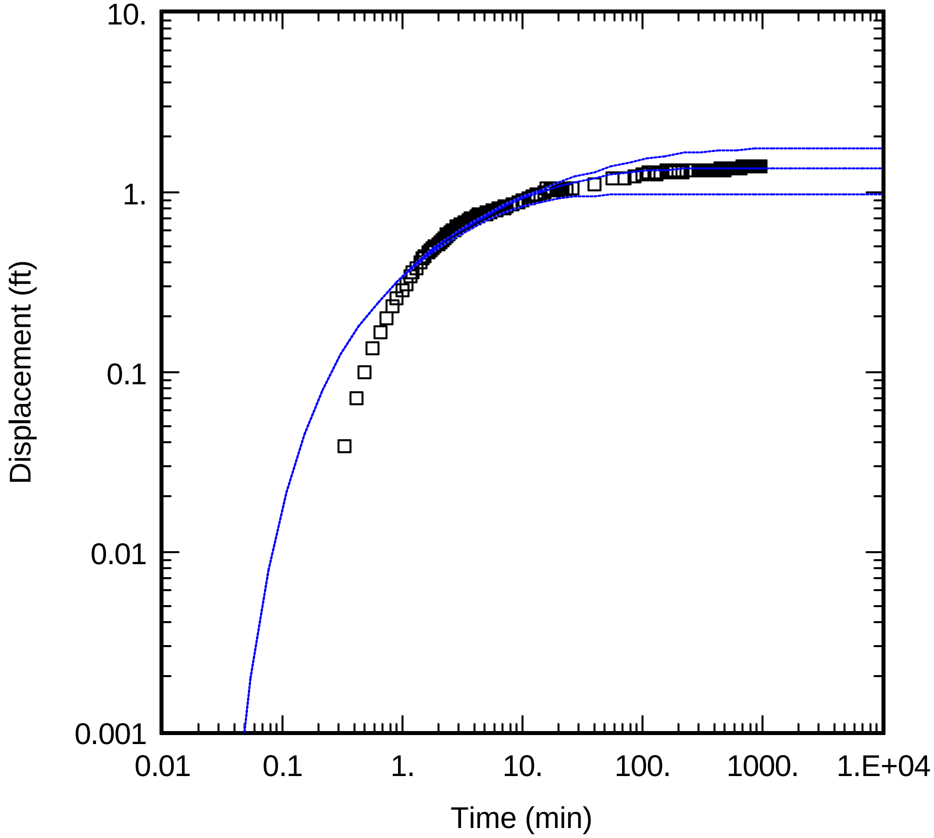
WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
A1-EW3B	1.212E+007	3.505E+006

Observation Wells

Well Name	X (ft)	Y (ft)
□ A1-MW8B	1.212E+007	3.505E+006



OBSERVATION WELL A1-P8

Data Set: C:\DOCUME~2\PROJECT\157392~1\APTDATA\A1-P8.AQT
Date: 06/21/02 Time: 11:28:58

PROJECT INFORMATION

Company: CH2M Hill
Client: US Navy
Project: 157392.LT.01
Test Location: Camp Allen Landfill
Test Well: A1-EW3B
Test Date: April 3-6, 2000

SOLUTION

Aquifer Model: Leaky
Solution Method: Hantush-Jacob

T = 2010.2 ft^2/day
S = 0.0001667
r/B = 0.1107

AQUIFER DATA

Saturated Thickness: 86.14 ft

Anisotropy Ratio (Kz/Kr): 1.

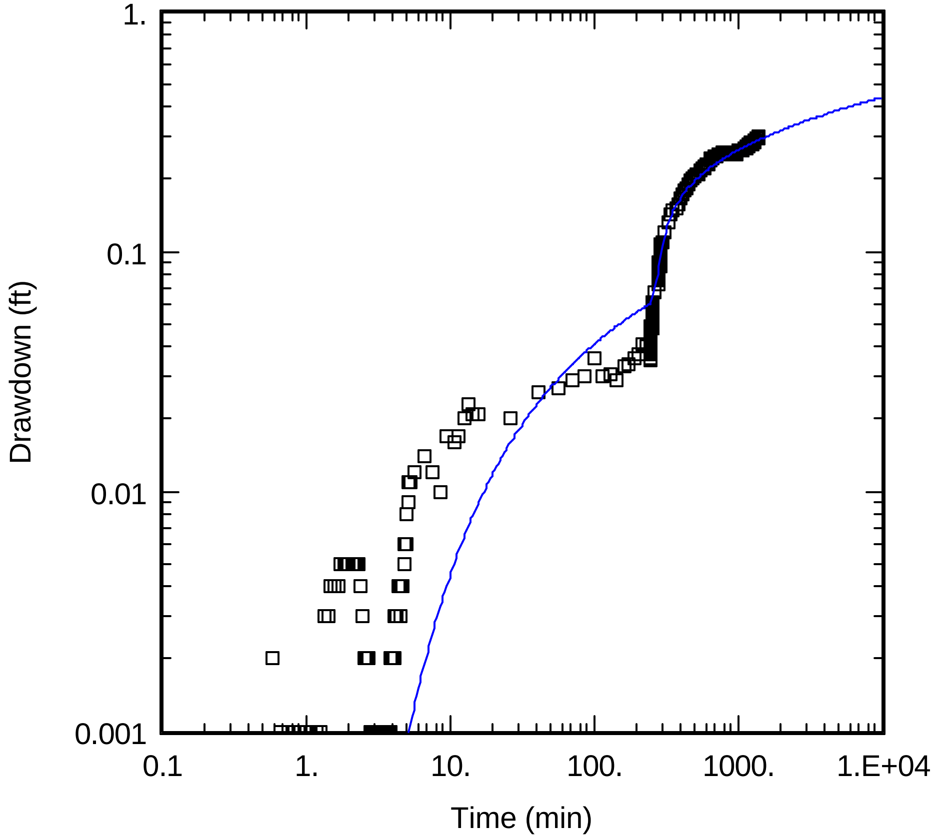
WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
A1-EW3B	1.212E+007	3.505E+006

Observation Wells

Well Name	X (ft)	Y (ft)
□ A1-P8	1.212E+007	3.505E+006



OBSERVATION WELL B-MW30

Data Set: C:\DOCUME~2\PROJECT\157392~1\APTDATA\B-MW30JG.AQT
Date: 06/21/02 Time: 11:28:20

PROJECT INFORMATION

Company: CH2M HILL
Client: Naval Station Norfolk
Project: 157392.LT.ZZ
Test Location: Camp Allen Landfill
Test Well: B-EW4A
Test Date: April 12, 2000

SOLUTION

Aquifer Model: Confined
Solution Method: Theis

T = 1307.1 ft^2/day
S = 0.004557

AQUIFER DATA

Saturated Thickness: 23.5 ft

Anisotropy Ratio (Kz/Kr): 1.

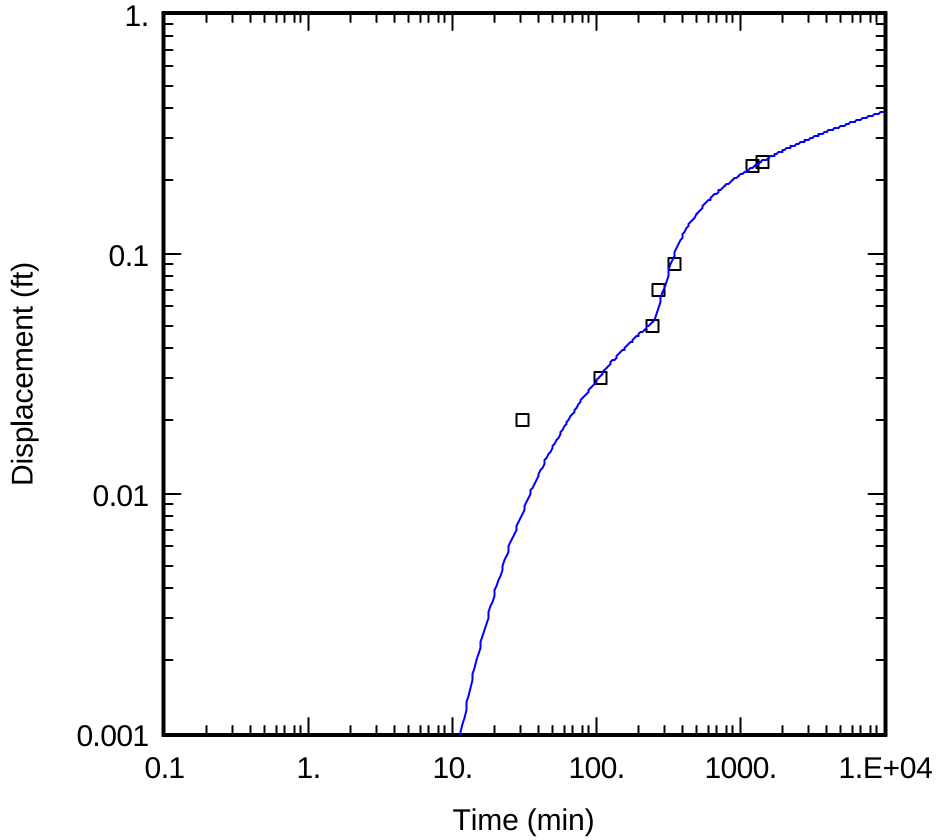
WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
B-EW4A	1.213E+007	3.506E+006

Observation Wells

Well Name	X (ft)	Y (ft)
□ B-MW30	1.213E+007	3.506E+006



OBSERVATION WELL B-MW32

Data Set: C:\DOCUME~2\PROJECT\157392~1\APTDATA\B-MW32JG.AQT
Date: 06/21/02 Time: 11:27:57

PROJECT INFORMATION

Company: CH2M HILL
Client: Naval Station Norfolk
Project: 157392.LT.ZZ
Test Location: Camp Allen Landfill
Test Well: B-EW6A
Test Date: April 12, 2000

SOLUTION

Aquifer Model: Confined
Solution Method: Theis
T = 1058. ft^2/day
S = 0.06345

AQUIFER DATA

Saturated Thickness: 24.1 ft

Anisotropy Ratio (Kz/Kr): 1.

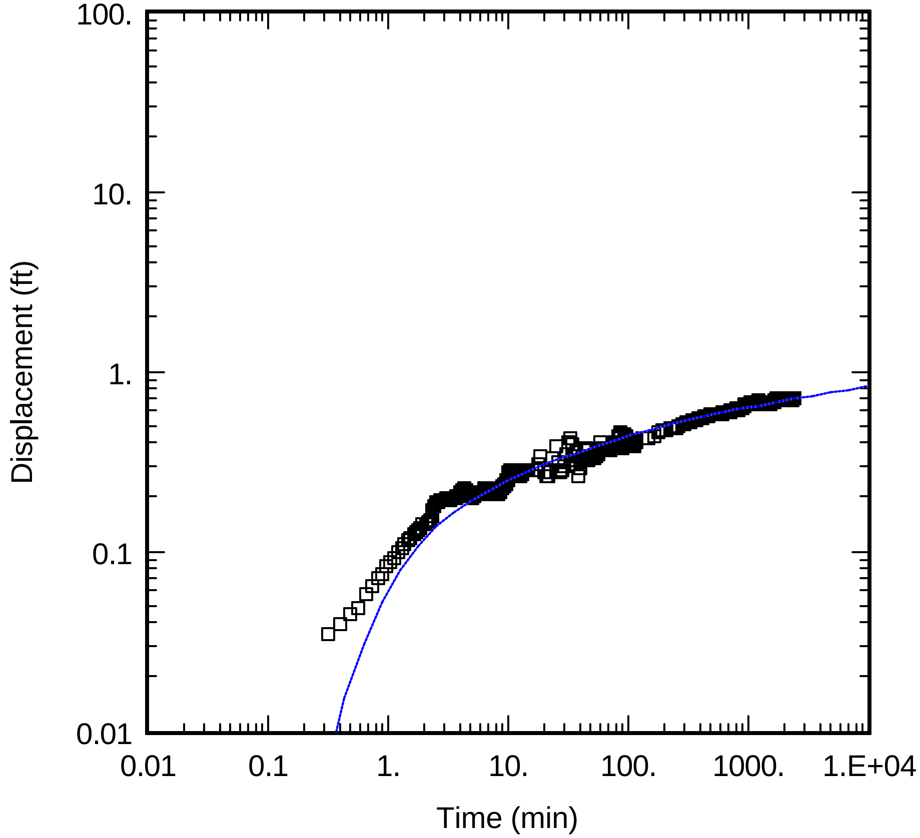
WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
B-EW6A	1.213E+007	3.506E+006

Observation Wells

Well Name	X (ft)	Y (ft)
□ B-MW32	1.213E+007	3.506E+006



OBSERVATION WELL B-MW33B

Data Set: C:\DOCUME~2\PROJECT\157392~1\APTDATA\B-MW33B.AQ
Date: 06/21/02 Time: 11:28:40

PROJECT INFORMATION

Company: CH2M Hill
Client: US Navy
Project: 157392.LT.01
Test Location: Camp Allen Landfill
Test Well: B-EW3B
Test Date: March 28-31, 2000

SOLUTION

Aquifer Model: Leaky
Solution Method: Hantush-Jacob

T = 1105.6 ft^2/day
S = 0.001754
r/B = 1.E-10

AQUIFER DATA

Saturated Thickness: 90.85 ft

Anisotropy Ratio (Kz/Kr): 1.

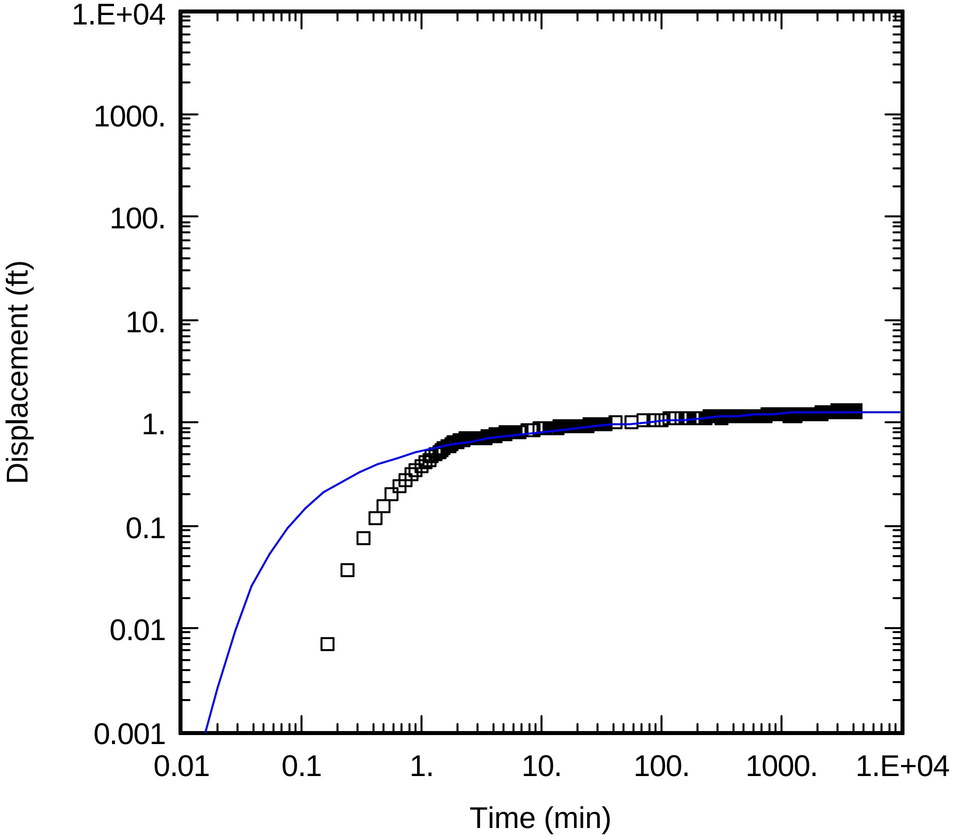
WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
B-EW3B	1.213E+007	3.506E+006

Observation Wells

Well Name	X (ft)	Y (ft)
□ B-MW33B	1.213E+007	3.506E+006



OBSERVATION WELL B-MW34B

Data Set: C:\DOCUME~2\PROJECT\157392~1\APTDATA\B-MW34B.AQ
Date: 06/21/02 Time: 11:28:30

PROJECT INFORMATION

Company: CH2M Hill
Client: US Navy
Project: 157392.LT.01
Test Location: Camp Allen Landfill
Test Well: B-EW4B
Test Date: April 3-6, 2000

SOLUTION

Aquifer Model: Leaky
Solution Method: Hantush-Jacob

T = 856.7 ft^2/day
S = 0.001638
r/B = 0.01126

AQUIFER DATA

Saturated Thickness: 94.6 ft
Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
B-EW4B	1.213E+007	3.506E+006

Observation Wells

Well Name	X (ft)	Y (ft)
□ B-MW34B	1.213E+007	3.506E+006